Layered Data Aggregation in Cell-Phone based Wireless Sensor Networks

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Abstract

The ubiquitous use of mobile phones motivates the idea of 'participatory sensing' with a cell-phone based sensor network. In our work, we consider a layered architecture for a query-based urban monitoring application using mobile phones. The key contribution of the paper is a Data-Aware Layered Waiting (DA-LW) time aggregation protocol in cell-phone based wireless sensor networks. To motivate the DA-LW protocol, we first develop a Cluster-Head (CH) based data aggregation protocol. The performance of the proposed protocols is evaluated in terms of energy, delay and resolution, which are primarily important for the monitoring application. Simulation results demonstrate the overall superiority in performance of the Data-Aware Layered Waiting algorithm over the Cluster-Head based algorithm.

Index Terms: Ubiquitous Sensor Networking, Data Aggregation

1. Introduction

Cell phone based sensor networks comprise of sensors embedded on hand-held devices, built upon the existing cellular framework [8], [7]. The advantages of such networks are: ubiquitousness of sensor nodes, coverage improvement, absence of issues related to deployment or means of providing energy to mobile nodes and most importantly, the involvement of the human user in collection of data [1]. Cell-phone based sensor networks can cater to applications like environmental monitoring, urban planning, natural resource management, tourism, civic hazard information sharing (nuclear, chemical, biological), crime patrolling etc. in a profound sense [14].

In our work, we consider an urban monitoring application of a cell-phone based sensor network. The sensed data can be temperature, humidity or a pollutant toxicity level. The ubiquitous nature of the sensor nodes (cell-phones) makes it necessary to develop efficient means of gathering sensed data, at the Base Station (BS) from the network, prior to its analysis at a database. Data aggregation helps avoid congestion in the network and reduces buffer requirements for sensor data at nodes. The aggregation algorithms must be designed to cater to the dynamic nature of the network. The performance of data aggregation schemes for monitoring applications can be evaluated based on:

- Energy drainage: The algorithm must be energy efficient to not weigh upon the regular use of cell-phones for voice/data communication.
- Delay: For applications like event detection this parameter is critical in indexing ubiquitous data aggregation schemes.
- Resolution of data: Even while optimizing on energy consumed and delay, the data obtained after in-network processing, must provide sufficient data resolution.

In geosensor networks, Data Aware clusters are created where nodes are grouped based on geographical proximity and similarity of measurements in order to improve the statistical quality of aggregated data [11]. In our work, we consider a zonal partitioning of the monitored area, which is virtually divided into sectors, further partitioned into layers. Here, zones are regions indexed by the same (layer, sector) such that nodes within a zone may sense data with sufficient correlation. The number of layers is decided at the BS based on the node density and the zones that can be identified in the city. The layer widths are chosen to ensure an equal distribution of nodes in each layer.

Note that in earlier work proposed in literature, an architecture suitable to ensure that data samples are obtained from all regions in the network has not been considered. Layering with equal layer widths does not ensure this for the typically observed Random-Waypoint distribution of nodes in an urban area. The zonal architecture considered in this paper takes into account the uneven distribution of mobile users in the Random-Waypoint node distribution and ensures...
data sample procurement from all regions of the network. In this paper, we propose a novel Data Aware Layered Waiting (DA-LW) time based aggregation algorithm for layered cell phone based sensor network. Here, each node computes its own waiting time based on its layer number and velocity. During this time, the node waits to receive packets for aggregation from other nodes in the same layer. In order to develop DA-LW for the layered Cellular Network, we first propose a Cluster Head (CH) based aggregation algorithm for this architecture. Clustering mechanisms in sensor networks have been extensively researched in literature [2], [5], [13]. In [10], clustering of mobile nodes is done to guarantee a probability of path availability within a cluster, while the B-protocol is proposed in [2]. In [12] mobility indices are computed for nodes in a distributed manner to aid in routing and cluster head selection. [5] and [13] present cluster head selection methods based on a weighted combination of power, mobility and transmission range of nodes. The proposed CH based algorithm is also weight-based, but is fully distributed with no explicit weight knowledge of its neighbors. The weight computed by each node depends on its energy, location and instantaneous velocity. Depending on single-hop or multi-hop transmission of aggregated data from CH to the BS, we classify the CH based on single-hop or multi-hop transmission of aggregated data. The weight computed by each node depends on its energy, location and instantaneous velocity. Depending on single-hop or multi-hop transmission of aggregated data from CH to the BS, we classify the CH based algorithm as CH based Single hop Cellular Network (CH-SCN) and CH based Multi hop Cellular Network (CH-MCN) respectively. A structure-free, location-aware, data aggregation protocol with randomized waiting at nodes is presented in [6]. The proposed DA-LW algorithm is also structure-free, location-aware and supports an early aggregation in time. It however explicitly uses knowledge of layer (layer number), and the velocity, hence computed, in the routing aspects of the protocol, specifically designed for the layered architecture. A comparative study of the proposed protocols alone is currently made, because of the fairness in the scenarios in terms of the unique layering architecture, which is absent in protocols proposed earlier in literature. We evaluate the performance of the proposed algorithms for energy dissipated, recharging frequency, delay and the resolution of the aggregated data.

In Section II, we describe the propagation model, the battery drainage model and the layering architecture. In Section III the CH Based data aggregation algorithm for layered cell phone based sensor network is described as a precursor to our key contribution, the Data Aware Layered Waiting (DA-LW) time based aggregation algorithm presented in Section IV. The simulation results are discussed in Section V and Section VI concludes the paper.

2. System model

In this section, the general framework over which the layered architecture and the proposed aggregation algorithms have been developed, is described.

2.1. Propagation Model

The radio waves obey a path loss model given by [9]:

$$P_r(r) = \frac{P_t}{(4\pi r/\lambda)^2}$$

where, $P_t$, $P_r(r)$ are the transmitted power and the associated received power at a distance $r$ from the source, respectively. $\lambda$ is the wavelength of the RF signal. The cell-phone discontinuously transmits sensor data in Power classII with a maximum nominal effective radiated power of $2dBW$ [9].

2.2. Energy Model of mobile phones

In cell-phone based sensor networks, cell-phones lose communication energy in voice calls in addition to energy loss in communicating sensor data. Hence, we choose a simple model for battery drainage between sampling instants:

$$charge(t) = charge(t_1) - \frac{(t-t_1)C_{max}}{T_{max}}$$

where $C_{max}$ is the charge rating of the mobile phone and $T_{max}$ is the corresponding talktime rating. $charge(t)$ and $charge(t_1)$ are the residual charge at time $t$ and $t_1$, respectively, where $t_1 < t$ and $t - t_1$ is the time between sampling instants. At each sampling instant, however, the residual charge decreases further by an amount dependent on the aggregation algorithm.

2.3. Layering Architecture

The area that needs to be monitored is assumed to be a circular disk for simplicity of analysis of the aggregation algorithms. The steady-state distribution of mobile nodes is assumed to be a Random Waypoint Mobility (RW) model [4]. For a unit disk area, the probability density of the time-stationary distribution of mobile node location, $M(t)$ as a function of radial distance $r$ from the center is [3]:

$$f_{M(t)}(r) = \frac{45}{32\pi}(1 - r^2)E(r^2)$$

In (3), $|r| \leq 1$ and $E(r^2)$ is the complete elliptic integral of the second kind. It is defined as:

$$E(r^2) = \int_0^{\pi/2} \sqrt{(1 - r^2 \sin^2(\theta))}d\theta$$
Owing to the $RW_P$ distribution, equal layer widths may lead to non-procurement of samples from higher layers and coarse resolution in lower layers. This motivates the proposed layered architecture. Unequal layer widths are chosen within a sector so that the probability of node occurrence in each layer is equal as in Fig. 1. The number of sectors can be chosen similar to the manner in which sectoring is typically done at the BS considering the site-map of the area and the desired capacity of cell-phone users in a sector. The number of layers $L$ within a sector, depends on:

- Number of mobile users in the sector: Let $n_l = \frac{N}{T}$, be the average number of nodes per layer, where $N$ is the total number of nodes in the area and $L$ is the number of layers. To keep $n_l$ a constant, if $N$ is less $L$ must also be decreased (and vice-versa) in order to guarantee an application-specified resolution for a given aggregation algorithm.

- Number of identifiable zones: If $N$ is high, $L$ can also be high for covering a particular area. However, this choice of $L$ may not be the best in terms of algorithmic overhead (communication) of the layered architecture. This is true especially if there are consecutive layers with nodes sensing highly correlated data due to similar urban environments [11].

Once $L$ is fixed, for a unit disk area with $q_L = 1$, the layer widths can be determined for $l = 1, 2 \cdots L - 1$ based on the condition that equal node occurrence probability in all layers is required:

$$\int_{q_{l-1}}^{q_l} f_M(r) 2\pi r \, dr = \frac{1}{L} \quad (5)$$

From the normalized layer outer radii obtained above, the actual layer radii are obtained by mapping these distances onto the area of interest.

### 2.4. Some general remarks about the proposed architecture

Since sectoring is usually done in cell-phone based networks, an additional layering based on the observed typical distribution of cell-phone users in urban areas will not be difficult, considering the advantages it gives in aggregating and routing for a typical monitoring application. The comments made here, take into consideration the fact that future technology (3G, 4G) promises further empowerment of hand-held devices, considering their ubiquitousness and potential use for various urban applications [1], [7].

- The cell-phone users are mobile at moderate speeds and the topology is virtually static for a period at least equal to the delay of the aggregation protocol.

- Energy can become a limitation for the cell phones and recharging is done for a practical residual charge threshold of \(\frac{1}{T}\) (maximum charge).

- Aggregation involves simple averaging operation with high-performance DSP processors. Cell phone receivers are capable of segregating data received from other nodes, at the packet level.

- The Base Station gives location and zonal (layer) information to each cell phone through a dedicated control channel. We assume that the BS has a dedicated control channel with each user, as in existing networks. Data can however be conveyed through single-hop or multihop in the network. Nodes compute velocity from consecutive location estimates obtained from the BS.

- The monitoring application is query-based. It requests for samples at the BS, specifying the area of interest, the frequency of data collection and the maximum delay constraint on the reception of data at the BS from the region of interest. The BS sends the query to all cell phones (through SMSs) in the sector of interest.

- The cell phone users provide sensor data only when queried by the Base Station and all cell phone users in a sector are assumed to be cooperative (neglecting policy and security related issues). All nodes in a sector are assumed to receive the query at around the same time. Further, the software on the cell phone can be programmed to collect and transmit samples as dictated by the aggregation algorithm.

- The effect of fading, multipath and multi-hop communication within zones have not been considered. Analysis of shape and size of zones, has not currently been made and have been approximated by hard boundaries as in Fig. 1.

- Precision errors in computations made in cell-phones have been neglected in order to primarily focus on the working and comparison of the proposed protocols.
3. Cluster Head (CH) based Layered Data Aggregation

Choosing a cluster head (CH) for each spatial zone will be a straightforward solution for data aggregation, in order to reduce communication overhead and congestion. For the mobile scenario, CH selection must be done everytime a query arrives and it needs to be a distributed process in order to reduce the overhead of maintaining and updating the structure. In this section we propose a distributed CH selection process for the layered architecture.

- On receiving the query, each node $i$ starts a timer value given by:
  \[ \text{timer}(i) \propto \frac{r(i)v(i)}{E(i)} \]
  where $r(i)$ is the radial distance of the node from the BS, $v(i)$ is its instantaneous velocity (the time index has been dropped for brevity), and $E(i)$, its residual energy.

- CH must have low location uncertainty and hence low velocity [12], and must be preferably close to the BS to reduce communication costs. Energy awareness is also incorporated in the timer value, to favor the node with more energy to be CH.

- The node whose timer expires first amongst nodes in a particular layer, is most suitable to be CH of the layer. It broadcasts a $CH_{\text{declare}}$ packet, conditioned on not "hearing" a $CH_{\text{declare}}$ packet from any other node in the same layer. The $CH_{\text{declare}}$ packet contains the $[\text{layer number}, \text{location}]$ of the node that declares itself as CH. All other nodes in the same layer, terminate their timers and send their sensed data to the self-elected CH. The timer value is normalized and the proportionality constant is chosen to ensure adequate time resolution between the timer values of different nodes to also account for time taken by the $CH_{\text{declare}}$ packet to travel across the zone.

- Nodes of a particular layer send the sensed data to the CH of that layer which aggregates the data into a packet containing two fields: the $[\text{average data value}, \text{layer number}]$. In our work we evaluate performances of both Cluster = Head based Single-hop ($CH-SCN$) and Multi-Hop Cellular Networks ($CH-MCN$), as shown in Fig. 2 and Fig. 3, respectively. In $CH-SCN$, aggregated data is sent to the BS directly by the CH of each layer, while in $CH-MCN$, aggregated data is sent to the CH of the next lower layer by a Request To Send ($RTS$) − Clear To Send ($CTS$) handshaking. The $CTS$ contains the node ID and location information of the CH of the lower layer. However, note that in $CH-MCN$ we have considered single-hop communication from nodes to CH of the corresponding layer to reduce delay overhead within the zone. Let $CH_1, CH_2 \cdots CH_L$ denote the Cluster Heads of layers $1, 2 \cdots L$, respectively. CHs do not aggregate the packet they receive from the CH of the lower layer with their own packet as they belong to different zones. In $CH-MCN$, $CH_l$ therefore sends $L + 1 - l$ packets to $CH_{l-1}$.

3.1. Energy and Delay Computations

In $CH-SCN$, power dissipated, $P_{d,SCN}(l)$ for a single layer, $l$ is given by

\[ P_{d,SCN}(l) = \sum_i P_T(i \rightarrow CH_l) + P_T(CH_l \rightarrow BS) \]

where $i \in K_l$ and $K_l$ is the set of all nodes in layer $l$. Note that the set is dynamic as the nodes are mobile. $P_T(i \rightarrow CH_l)$ and $P_T(CH_l \rightarrow BS)$ are the transmitted energy from node $i$ to the CH of layer $l$, and from $CH_l$ to BS, respectively.

In $CH-MCN$, power dissipated, $P_{d,MCN}(l)$ for a single layer, $l$ is given by

\[ P_{d,MCN}(l) = \sum_i P_T(i \rightarrow CH_l) + (L+1-l)P_T(CH_l \rightarrow CH_{l-1}) \]

where $P_T(CH_l \rightarrow CH_{l-1})$ is the transmission energy for a single packet from $CH_l$ to $CH_{l-1}$ and $L + 1 - l$ is the number of packets transmitted from layer $l$ to $l-1$. The total

\[ \frac{r(i)v(i)}{E(i)} \]

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power dissipated in the sector is the sum of power dissipated in all layers both in the case of \( CH - SCN \) and \( CH - MCN \). In \( CH - SCN \), delay \( T_{SCN}(l) \) within layer \( l \) is given by

\[
T_{SCN}(l) = \min(\text{timer}(i)) + \frac{\max(\text{dist}_{i-CH_L})}{c}
\]

where the first term is the minimum timer value of all \( i \in K_l \) and the second term is the time taken for the last data packet within layer \( l \) to reach \( CH_L \), \( c \) is the velocity of radiowave propagation and \( \max(\text{dist}_{i-CH_L}) \) is the distance of the farthest node amongst all \( i \in K_l \) from \( CH_L \). The maximum delay (neglecting delays in processing and control packet exchanges) in propagating the \( L \) data packets to BS is

\[
T_{SCN} = \max(T_{SCN}(l)) + \frac{\max(\text{dist}_{CH_L-BS})}{c}
\]

where layer \( l \) has the longest delay in the clustering phase and the \( CH_L \) takes longest to deliver its aggregated packet, being farthest from the BS.

In \( CH - MCN \), \( T_{MCN}(l) = T_{SCN}(l) \) and the total delay in delivering \( L \) packets is

\[
T_{MCN} = \max(T_{MCN}(l)) + \sum_{i=1}^{L}(L+1-l)\frac{\text{dist}_{CH_L-CH_{l-1}}}{c}
\]

. The second term is the sum of the delays in relaying packets across layers.

4. Data-Aware Layered Waiting time based Data Aggregation algorithm

In Section IV, a straightforward solution was proposed for gathering and aggregating data within zones. But having a single \( CH \) waiting long enough to collect samples from all cooperating nodes in its layer may not be appropriate with respect to resolution and delay. In this section, we present a non-\( CH \) based aggregation algorithm where nodes aggregate data received from other nodes in the same layer (making the algorithm Data Aware). Each node waits for a duration depending on its layer number and instantaneous velocity in order to receive data from other nodes in the same layer for aggregation (Fig. 5). In [6], nodes have randomized waiting times for structure-free data aggregation. In our work, we however opt for a layered waiting time to suit the layering architecture for the cell-phone based sensor network.

- Consider a cell-phone \( i \) where \( i \in K_l \) of layer \( l \). On receiving the query, it computes a waiting time \( \tau_w(i) \) locally:

\[
\tau_w(i) = \alpha(i) \frac{d(l)}{c}
\]

where \( d(l) \) is the maximum distance a packet may need to travel within layer \( l \) in a sector to get to a node which aggregates packets in layer \( l \), \( c \) is the velocity of radiowave propagation. \( d(l) \) is calculated geometrically from Fig. 4 as follows:

\[
a(l) = q_i \sin(\frac{\pi}{S})
\]

\[
h(l) = \text{width}(l)\sin(\frac{\pi}{2} - \frac{\pi}{S})
\]

\[
m(l) = \text{width}(l)\sin(\frac{\pi}{S})
\]

\[
d(l) = \sqrt{h(l)^2 + (2a(l) - m(l))^2}
\]

where \( q_i \) is the outer radius of layer \( l \) with origin at the BS and \( \alpha(i) \) is a node-specific constant factor which depends on the velocity of node propagation. Here we use the fact that a node moving with lower velocity has lower location uncertainty and can wait for a packet transmitted by a node located far from itself in the same layer. However, a node moving with higher velocity must wait only for a shorter time to gather data from other nodes in the same layer due to its higher location uncertainty.

\[
\alpha(i) = \frac{1 - \frac{v(i)}{v_{max}}}{S}
\]

where \( v_{max} \) is the maximum node velocity.

- Having calculated the waiting time, \( \tau_w(i) \), node \( i \) computes \( \tau_q(i) = \frac{\tau_w(i)}{10} \). At a time \( \tau_q(i) \) after receiving the query, node \( i \) broadcasts a \( \tau_w \), declare packet which contains the triple \([\text{layer number}, \text{location}, \tau_w(i)]\) in its fields. \(^1\) It then starts the timer \( \tau_w(i) \), waiting for the arrival of data packets from other nodes. Note that the waiting duration is measured only from the instant the

\(^1\)Note that negligible computation time is assumed in comparison to the waiting time.
Let $\tau_w, \text{declare}$ has been broadcast. The parameter $\tau_d(i)$ has been made dependent on $\tau_w(i)$ in order to ensure different transmission instants of $\tau_w, \text{declare}$ packets by different nodes.

- If any node $j$ in layer $l$ hears the $\tau_w, \text{declare}$ of node $i$ in the same layer $l$, and it meets the following condition, it sends its sensed data to node $i$:

$$r_{ij} \leq \frac{c\tau_w(i)}{2}$$  \hspace{1cm} (13)

$r_{ij}$ is the Euclidean distance between node $i$ and node $j$. If node $j$ "hears" the $\tau_w, \text{declare}$ packets of node $i$ and node $k$ (where $k$ also belongs to layer $l$) simultaneously, and $r_{kj} \leq \frac{c\tau_w(k)}{2}$ also holds true, then for $\tau_w(k) > \tau_w(i)$, node $j$ sends its packet to node $i$. This means that nodes favor packets to get aggregated "early in time", within a layer attempting to reduce delay of the aggregation protocol.

- The above steps are implemented for all nodes in layers $l = 1, 2, \ldots, L$, in the sector of interest. Nodes that send packets to other nodes for aggregation set their $\tau_w$ values to 0. Nodes that receive packets for aggregation send the averaged value and their own node IDs to the BS over single-hop after which they set their $\tau_w$ values to 0.

- Due to poor connectivity, some nodes in layer $l$ may not meet the condition (13) and have $\tau_w \neq 0$. These nodes transmit their data directly to the sink node with [data, layer number, node ID].

- Let $\tau_{w,\text{max}}$ be the maximum waiting time of the nodes in the sector and let $i'$ be the node with $\tau_w = \tau_{w,\text{max}}$. If $r(i')$ is its distance from the BS, and if it has not transmitted its data to any other node in its layer for aggregation, an upper bound on the delay would be:

$$T_{DA-LW} = \max(\tau_w) + \frac{r(i')}{c}$$

5. Simulation Results and Discussion

In this section, the two algorithms are evaluated for various parameters of interest in a cell-phone based framework. Note that comparison has been made between the two proposed algorithms only, as no other readymade algorithms are available in literature specifically designed for the layered architecture. The simulations have been performed for the case of 400 nodes deployed in a circular area of radius 1000 m. The Random Trip mobility model is used [4] to simulate node movement. The velocity range is $0.01 - 9.99$ m/s and the pause time is uniformly distributed between 0 – 100s. The number of layers, $L = 6$ and sector number $s = 4$ of the $S = 8$ sectors is considered. The battery rating is chosen as $3.7 \times 1250$ mAh and users are assumed to recharge their batteries if the charge falls below $0.2 \times \text{battery rating}$. Each user is also assumed to have a different battery charge at the start of the simulation. Collection of data to be monitored is done at 10 minute intervals, and the performance of the algorithms is studied over a period of 100 minutes. The cell phone receiver sensitivity is chosen to be $–60 \text{dBm}$.

![Figure 6. Comparison of energy dissipated in a sector](image-url)
opposed to the CH based schemes having a single CH per layer. This is despite the fact that the overall energy dissipation of DA−LW is higher than the CH based schemes (Fig. 6).

A comparison of the delays in collecting aggregated data from all the L layers at each sampling instant is shown in Fig. 9. As expected, the DA−LW scheme has lesser delay than the CH based schemes as nodes transmit their data to other nodes in their vicinity who have lower waiting times than themselves. Also, each node waits only for a time related to its velocity unlike in CH, where the cluster head waits to receive data from all nodes in its layer. The CH−MCN has more delay than the CH−SCN algorithm as the BS needs to wait for all the L samples to be relayed through the CHs in multiple hops. (Note that processing delays have been neglected for all the schemes).

The number of aggregating sources for each layer is an important parameter to decide the resolution of data from each layer. It is given by

$$\text{resolution}(l) = \frac{k(l)}{n(l) \times \text{area}(l)}$$

where $k(l)$ is the number of samples transmitted from layer $l$ to BS after aggregation, $n(l)$ is the number of nodes in layer $l$ with data samples to be aggregated and $\text{area}(l)$ is the area of layer $l$. For $l = 2, 3 \cdots L$

$$\text{area}(l) = \pi \left( \frac{q_l^2 - q_{l-1}^2}{2} \right)$$

and $\text{area}(1) = \pi q_1^2$. As can be seen from Fig. 10 resolution(l) is higher for DA−LW compared to CH based schemes, where $k(l) = 1$.

For monitoring applications, we can further quantify the performance by $\text{Efficiency} = \frac{\text{samples}}{\text{area} \times \text{cost}}$ where $\text{cost} = \text{Energy} \times \text{delay}$. Fig. 11 shows that the DA−LW scheme has higher efficiency than the CH based
scheme in all sampling instants.

6 Conclusion

In this paper we consider a monitoring application of cell-phone based sensor networks over a layered architecture and propose two data aggregation algorithms for the same. Our key contribution is the Data Aware Layered Waiting (\textit{DA} – \textit{LW}) time based aggregation algorithm for the layered architecture. Its performance is compared to a novel Cluster – Head (\textit{CH}) based data aggregation algorithm where the \textit{CH} selection is done in a distributed manner. \textit{CH} has been evaluated for both single-hop (\textit{CH} – \textit{SCN}) and multi-hop cellular networks (\textit{CH} – \textit{MCN}) and it gives low energy dissipation in the network at the cost of higher delay as compared to the proposed \textit{DA} – \textit{LW}. The absence of a pre-defined structure in \textit{DA} – \textit{LW}, results in \textit{DA} – \textit{LW} having a higher resolution than \textit{CH}. Other aspects of these algorithms related to varying transmission ranges, load balancing and packet loss need to be further analyzed. It would be interesting to consider issues related to monitoring applications for high mobility scenarios for further research.

References