Distance-based Cluster Head Election for Mobile Sensing

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Distance-based Cluster Head Election for Mobile Sensing

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Abstract—Energy-efficient, fair, stochastic leader-selection algorithms are designed for mobile sensing scenarios which adapt the sensing strategy depending on the mobile sensing topology. Methods for electing a cluster head are crucially important when optimizing the trade-off between the number of peer-to-peer interactions between mobiles and client-server interactions with a cloud-hosted application server. The battery-life of mobile devices is a crucial constraint facing application developers who are looking to use the convergence of mobile computing and cloud computing to perform environmental sensing. We exploit the mobile network topology, specifically the location of mobiles with respect to the gateway device, to stochastically elect a cluster head so that (1) different energy saving policies can be implemented and (2) battery lifetime is increased given an energy efficiency policy, in a fair way. We demonstrate that the battery usage can be made more fair by reducing the difference in battery life-time of mobiles by up to 66%.

Index Terms—Leader-Election; Mobile Sensing; Cloud Computing; Energy Efficiency; Battery Life-time.

I. INTRODUCTION

Smart phones with a range of increasingly sophisticated sensors provide an appealing network substrate for distributed environmental sensing [1]. Applications in the area of social networks, fitness trackers and environmental monitoring may harness this sensor data in order to meet high-level system objectives [2]. Current applications of this computing paradigm include acoustic monitoring and interference reduction [3]. A limitation of this paradigm is the battery-life of the mobiles that compose the network [4]. Battery-life determines the number of times a mobile can offload sensed data to a gateway. Whilst communication technologies, screen features, multimedia capabilities and processing power have increased, battery performance has not improved at the same speed [4].

Cluster Head (CH) election algorithms such as [5], [6], [7] are receiving increasing attention as they provide a mechanism for the network devices to collaboratively trade-off the number of costly transmissions they make over the cellular network with the number of less costly p2p transmissions (using a technology such as WiFi-Direct [8]). By cost we mean the frequency that this mobile becomes a CH, as transmissions to the other cluster members, it may be desirable to increase the CH election probability of the entire ensemble of mobiles to meet energy saving objectives.

Our investigation into a policy-based approach for energy consumption reduction is timely and of interest to the mobile sensing community. It meets one of the challenges most likely to arrest the wide-spread deployment of mobile sensing technology, namely battery-life. This paper is organized as follows. The scenario design constraints are set out in Section II. Power consumption costs are described in Section III. A CH election algorithm that implements the policies outlined above is described in Section IV. The efficacy of these approaches is evaluated and discussed in Section V.

II. SCENARIO: DESIGN CONSIDERATIONS

We focus on the benefits of deploying different sensing policies for CH election in open areas like a university campus, a park or a railway station. Fig. II illustrates a portion of a university campus. Mobiles, illustrated with circles, form the substrate for sensing in this area. These mobiles boast a number of p2p interfaces and a 3G interface [10]. The density
of mobiles in each area changes with time and space, a process which has been described previously using a Levy Walk [8]. This scenario gives rise to the need for a CH election procedure that implements different policies depending on the objectives of the network and the typical locations of mobiles.

Using mobiles as the substrate for mobile sensing is achieved by a number of enabling functions which are common to the technologies discussed here, WiFi, WiFi-Direct, 3G, etc. A network set-up phase may involve registration of the mobile with a gateway and the configuration of the mobile by the gateway. This may be achieved during a pre-deployment step, or during run-time whenever a mobile attaches itself with a gateway. The second function that is required here is CH election, for example LEACH [5]. The battery-life of the sensing substrate is crucially determined by the strategy used to determine when a mobile is a CH. Choosing one mobile to be a CH with a high frequency may cause the depletion of the mobile’s battery. As a result, the network may lose the ability to sense the region in which the mobile was located.

Routing, is required in order to determine how to traverse a dynamic topology, to deliver the sensed data to the gateway, and then the cloud-server. Functions such as security are not the primary consideration of our contribution, we acknowledge its importance and appeal to the state-of-the-art for its adequate provision. The focus of the investigation carried out in this paper is CH election. We only assign mobiles to CHs which are one-hop away, which simplifies routing.

Mobiles possess the ability to modulate their transmit power based on their distance from a gateway. The Universal Mobile Telecommunications System (UMTS), 3G mobile cellular system, uses Open Loop Power Control to set the uplink transmit power of the mobile. The Inner Loop Power Control regulates the UE’s ability to adjust its power in order to keep the received uplink Signal-to-Interference Ratio (SIR) at a target level. 3G’s Radio Resource Controller defines four states where the mobile experiences different data transmission performance and power consumption. Two of the highest, in order of highest to lowest power consumption, Dedicated Channel (DCH) and Forward Access Channel (FACH), are considered here. The granularity of changes in transmit power may be limited to 1, 2 and 3dB which limits the tunability of the transmit power in practice. We will assume that Location Services are on so that this information is available to compute transmission ranges in high accuracy, high speed mode, using GPS, WiFi and cellular networks. However even if this information is not available, a user’s location could be approximately identified by only leveraging sensors that did not require user permission. For example, the route a mobile takes may be described in terms of a series of turns, which are described by a specific direction and angle. By measuring the sequence of turns and mapping them to a city map, the user’s location could be inferred. In a more general setting the ability to measure distance between Internet-of-Things devices and mobiles is discussed [12], and thus, these things may provide alternative sources of location information.

Regarding p2p communications, WiFi-Direct was introduced in Android 4.0. Its power saving protocols are attractive compared to p2p technologies such as the ad-hoc mode of WiFi. The main difference between WiFi-Direct and WiFi is that WiFi-Direct does not need an access point. Mobiles forming a WiFi-Direct P2P group are either (1) Group Owners (GO), with similar functionalities to an AP or (2) a p2p client.

The ability to be able to tether mobiles is a key requirement if mobiles are to become CHs and to gather and redirect its cluster’s traffic. Android has offered tethering since version 2.2. Tethering is used in the present context to form a bridge between the 3G interface and any other p2p interface in order to share the CH’s 3G connection.

We have considered the problem of gas sensing in previous work [7]. Mobile phones come with a range of sensors: one accelerometer, a gyroscope, a magnetometer, a barometer, two cameras, a pedometer, a light sensor, a humidity sensor and up to four microphones and so a range of other use-cases may also be addressed. Compression of in-network signals may be achieved in various ways. Recent contributions [13] and [14] consider a combined learning and compression approach. We do not focus on compression, but instead assume that a frame of fixed size, $k$ bits, is sent from any CH or between peers.
is $d$ m. The energy dissipated by the transmit electronics for both the transmitter and the receiver is $E_e$ J/b. The energy dissipated in the transmit amplifier is $\epsilon J/b/m^2$.

During the transmission of bits, the energy consumed by the transmitter is composed of a transmit electronics component and a transmit amplifier component,

$$E_T(k,d) = E_e(k) + \epsilon kd^2. \quad (1)$$

At the receiver, the energy dissipated is

$$E_R = E_e(k). \quad (2)$$

**Multiple p2p Transmissions vs Long-range Transmission:**

Consider a network consisting of $N$ mobiles, $n = 1, 2, \ldots, N$, which are separated by $r$ meters. In Fig. $2$, $N = 6$. Each of these mobiles are points on the same line. The total energy dissipated by any mobile, which is $nr$ away from the BS, when it communicates with the BS is

$$D = k(E_e + \epsilon d^2) = E_e k + \epsilon k(nr)^2. \quad (3)$$

In Fig. $2$, $d = 6r$. In the p2p case each mobile sends a message to the next mobile on the way to the BS. The mobile located $nr$ meters from the BS requires $n$ transmissions, each of which is $r$ meters, and $n - 1$ message receptions.

$$M = nk(E_e + \epsilon r^2) + (n-1)E_e k = (2n-1)E_e k + nk\epsilon r^2. \quad (4)$$

To develop a base-line understanding of the need for p2p communications we consider when is $D = M$? This may be expressed as the equality

$$0 = -2E_e + n(2E_e + \epsilon r^2) - \epsilon r^2 n^2 \quad (5)$$

We solve for $n$

$$n = \frac{((2E_e + \epsilon r^2) \pm (2E_e - \epsilon r^2))}{2\epsilon r^2} \quad (6)$$

One solution is $n = 1$. In the second solution the ratio of the transmit electronics energy consumption to the transmit amplifier is crucial, along with the distance between mobiles.

$$n = \frac{2E_e}{\epsilon r^2}. \quad (7)$$

**Effect of distance from the Base-Station:** Consider the average p2p transmit energy, $\mu_p$, in the linear network in Fig. $2$ e.g. the average energy required to transmit to a neighbour who is up to a maximum of $I$ mobiles away. We assume that 1-hop is any distance up to a maximum distance of $Ir$ meters. To keep this argument simple, we assume that mobiles have a similar number of peers at different distances, some of the cases when this does not hold are illustrated in Fig. $3$. If the linear array is long enough the effect of these cases is reduced. The average p2p transmission energy is

$$\mu_p = \frac{k}{I} \sum_{i=1}^{I} (E_e + \epsilon r^2) = kE_e + k\epsilon r^2 \frac{(I+1)(2I+1)}{6} \quad (8)$$

If all mobiles are a CH with probability $p$, the approach taken by LEACH $[5]$, and the system evolves for $R$ epochs, then the total energy consumed by a mobile has a term for direct communications and for p2p communications:

$$pRD + (1-p)R\mu_p. \quad (9)$$

Assuming that the average p2p transmit energy is the same for all mobiles, we may compare the energy consumed by mobile 1 and mobile 6 by only considering the term $pRD$ as each mobile is a CH with equal probability

$$kP(R(E_e + \epsilon (6r)^2)) > kP(R(E_e + \epsilon r^2)). \quad (10)$$

We conclude that if all mobiles are equally likely to be CHs, mobile six’s battery will expire significantly earlier than mobile one’s battery. If the objective of the network manager is to deploy a fair mobile sensing function, choosing CHs with equal probability, irrespective of their distance from the BS will not satisfy this objective. Portions of the environment that are to be sensed, and that are far away from the BS, will be stopped being sensed sooner than other portions that are closer to the BS. We propose a distance-based fairness approach for modulating the CH probability of mobiles so that the shortcomings of approaches, for example $[5]$, are remedied.

**IV. Policy-based Election**

In the previous section we analyzed the (1) energy of p2p versus direct communication and (2) the effect of distance...
from the BS on battery-life. We now introduce election algorithms that consider the policies outlined above. On each mobile a pulse train, $s(t)$, stimulates the mobile to hold an election,

$$s(t) = \sum_{n=0}^{\infty} \delta(t - nT_i),$$  \hspace{1cm} (11)

The inter-election period is $T_i$ and $\delta(t)$ is a Dirac delta pulse. When $s(t) = 1$ an election is held. A counter then keeps a real-time record, $r(t)$, of the number of Dirac delta pulses that have arrived since $t = 0$. At time $t = t$

$$r(t) = \int_{0}^{t} s(t) dt.$$  \hspace{1cm} (12)

When $s(t) = 1$, a random trial is performed and a random variable $X$ is drawn from a uniform distribution $X \sim \mathcal{U}(0, 1)$. To determine if the mobile is a CH, the value of $X$ is compared with a threshold $T(t)$, which is computed as follows

$$T(t) = \frac{p}{1 - p \text{ mod}(r(t), \frac{1}{p})},$$  \hspace{1cm} (13)

where $\text{mod}(r(t), \frac{1}{p})$ computes $r(t)$ modulo $\frac{1}{p}$. The parameter $p$ is the probability that any mobile in the network is a CH and $r(t)$ is a count of the number of previous elections. A mobile becomes a CH if $x < T(t)$. In LEACH $p$ is the same constant value for all mobiles, for all points in time. We have highlighted the disadvantages of this approach. The threshold $T(t)$ is a saw-tooth-like function that builds memory into the CH election process. A number of periods of oscillation between small and large values are illustrated in Fig. 4. A high value of $x$ avoids CHs and mobiles are in the CH election process. A number of periods of oscillation between small and large values are illustrated in Fig. 4. When $x < T(t)$, a mobile becomes a CH if

$$x < T(t) = \frac{p}{1 - p \text{ mod}(r(t), \frac{1}{p})}.$$  \hspace{1cm} (12)

The inter-CH time in Fig. 5 is the time duration that passes between each time a mobile is a CH. When $p$ is small, the long period of $T(t)$ causes this inter-CH time to be large. The value of $p$ is crucial in determining the energy consumption of mobiles. **Distance-Based Fairness:** Mobiles that are far away from the BS expend more energy than mobiles that are close to the BS. Far away mobiles will expire faster, which will reduce the life-time of the mobile network. This problem is addressed by making the probability that each mobile is a CH a function of its distance from the BS. If the distances of mobiles $a$ and $b$ are $a$ and $b$ meters, respectively, and $a$ is further away from the BS than $b$, the energy consumption of these devices may be compared using the relation developed in Eqn. 10

$$\alpha_a E_c + a^2 > \alpha_b E_c + b^2.$$  \hspace{1cm} (14)

We relax the constraint that all mobiles have the same probability of being a CH. Instead, weights are be introduced, $\alpha_a$ and $\alpha_b$, for mobile $a$ and $b$, respectively. We assume that $E_c$’s effect on the transmission cost is dominated by the distance squared. To ensure that the transmission costs are approximately the same for both mobiles we select $\alpha_n$ for the $n$-th mobile to be

$$\alpha_n = \frac{p}{D d_n^2}$$  \hspace{1cm} (15)

where $d_n$ is the distance of mobile $n$ from the BS and $D = \frac{1}{N} \sum_{n=1}^{N} \frac{1}{d_n^2}$. The advantage of this approach is that the average of the weights $\alpha_n$ equals $p$ – consider that $\frac{1}{N} \sum_{n=1}^{N} p = p$, and therefore $\frac{1}{N} \sum_{n=1}^{N} \alpha_n$ should also equal $p$. The disadvantage is that $D$ must be known when an election is being held by mobiles involved in the election. This information may be communicated by the BS to the mobiles. Mobile motion is likely to be repetitive. We argue that an expected value of $D$ may be used, which reduces the frequency of updates of the value of $D$ from the BS to the mobiles. As energy consumption is heavily determined by the number of bits regularly transmitted, we note that broadcasting the value of $D$ to all mobiles is likely to only cost a few bits, and that the frequency of these broadcasts is likely to be low, given the physical constraints of the environment inhabited by the mobiles is likely to promote a relatively stable value of $D$.

**V. Numerical Evaluation**

We investigate the energy consumption of a mobile using a discrete event simulator, namely MATLAB’s SimEvents environment [17]. SimEvents extends the capabilities of MATLAB’s Simulink to Discrete Event Simulation (DES), which allows for the development of activity-based models to evaluate system parameters such as processing delays, resource contention and energy consumption [18], which is the focus of the next section.
of this evaluation. Mobiles are located in the environment described in Fig. 1 This building is 30m × 20m. The BS is 1km away, facing out from the living area. We investigate the performance of the distance-based fairness CH formation algorithm versus our baseline method [5]. Given that we are investigating the power consumption of the CH reporting process (which is comprised of the energy consuming components in the discussion above), we report the results in terms of DES run-averages of specific mobiles in depth, as opposed to the aggregate performance of the entire ensemble, as the decision to form a CH is taken at each mobile independently of the other mobiles. For the distance-based fairness approach we examine mobiles at different locations in the network for an arbitrarily long period of time—the length of time it takes a mobile’s battery to expire— as the complexity of the system and the computation power required are both reduced.

Energy Consumption Considerations - Base-line: We assume that the energy of a fully charged mobile battery is 29000 J. A typical mobile battery is 2000mAh. We assume a voltage of 4V; therefore, 1 milli-amp hour is 0.001 × 4 × 60 × 60 = 14.4J. We use the constants $E_e = 50 \times 10^{-9}J/b$ and $\epsilon = 100 \times 10^{-12}J/b/m^2$ in our simulations.

The energy of the battery is limited to approximately 20% in order to limit the portion of battery that is allocated to mobile sensing. If the mobile’s sensing energy budget is limited to 6000J, what is the time taken for the mobile’s battery to expire for $p = 0.01$, $p = 0.05$ and $p = .1$ using the base-line CH formation approach? Fig. 6 illustrates the consumption of energy for the first 100s of the life of three mobiles under the three CH formation regimes, e.g. $p = .1, .05$ and .1 in order to demonstrate the energy consumption effect of direct compared with p2p communications (cf. the depth of the step-increases in these time-series). When the probability $p$ is large, the mobile is a CH more frequently; therefore, it makes more direct communications with the BS and the battery is depleted faster. In this scenario the BS is 1km away from the building and the neighbouring mobiles are on average 10m away from each other.

In order to compute the average time it takes for a mobile’s battery to expire, $t_e$ for different values of $p$, we find the coefficients of a polynomial of degree-1, $e = p_1 t + p_0$, that fit the cumulative energy consumption readings, $e$, in a least-squares sense for multiple runs of the DES. Our estimate of the average time it takes a mobile to expire is then

$$t_e = \frac{e - p_0}{p_1}. \quad (16)$$

The longer it takes for the mobile’s battery to expire, the longer the network may be sensed. Assuming that CH election and reporting is the only function that consumes battery life Table 1 summarizes the life-time of the battery. Increasing $p$ by a factor of 5 from $p = 0.01$ to $p = 0.05$ decreases the battery-life by a factor of three. Increasing $p$ by a factor of ten to $p = .1$ decreases the battery life by a factor of 5. This energy consumption gain is explained by examining the number of times each mobile is a reporting CH mobile, e.g. 246, 786 and 1206 times, as $p$ increases. The number of bits reported by each mobile has a large effect on the battery-life of each mobile.

Distance-based Fairness: The objective of distance-based fairness is to minimize the variance of $t_e$ across the ensemble of sensing mobiles. To demonstrate the efficacy of distance-based fairness we consider the battery-life of a mobile which is 1km from the BS (relatively close to the BS) and mobile which is 1036m away from the BS (relatively far away). These mobiles are stationary. We position 100 other participating mobiles on average 1km from the BS with a standard deviation of 10m.

Fig. 7 illustrates that when distance-based fairness is not used the lifetime of mobiles at different distances from the BS depends on this distance. As a consequence parts of the sensing topology may run out of battery before other parts. The battery life-time for both mobiles running distance-based fairness is approximately the same, which indicates that the energy consumption costs are shared more fairly.

TABLE I

<table>
<thead>
<tr>
<th>$k$ in $\text{m}$</th>
<th>$p = 0.01$</th>
<th>$p = 0.05$</th>
<th>$p = 0.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15400 days</td>
<td>5114 days</td>
<td>3409 days</td>
</tr>
<tr>
<td>1036</td>
<td>15.4 days</td>
<td>5.114 days</td>
<td>3.409 days</td>
</tr>
<tr>
<td>CH</td>
<td>246</td>
<td>786</td>
<td>1206</td>
</tr>
</tbody>
</table>

Fig. 6. Cumulative sum of the energy consumed transmitting 1 bit for $p = .1, .05$ and 0.01. Direct transmissions to the BS consume significantly more than p2p communications. These time-series increase monotonically.
that is closer to the BS lasts 214 days longer, assuming 1bit is transmitted. The direct communication cost is higher for the mobile 1036m away from the BS, therefore its battery expires first. In comparison when both mobiles use distance-based fairness the lifetime of both mobiles differs by 75 days, which is a fairer allocation of the reporting load. The previous difference in life-time of 214 days has been reduced by 66%. However in the distance-based fairness approach the lifetime of both mobiles is reduced due to the division by $D$ in the CH probability update rule in Eqn. [5] In order to correct for this we change the CH probability $p$ to $p = 0.07$ in Table II. The number of times that the mobile that is 1km from the BS is elected to be a CH changes from 1299 (when $p = .1$) to 1034 (when $p = .07$) which is approximately equal to 1086 when distance based fairness is not used. Table III summarizes the battery lifetime of the two mobiles under different CH election regimes and the number of times that each mobile is elected to be a CH.

The distance-based fairness protocol that we proposed here is scalable. The computational complexity and messaging complexity of the protocol grows at a sustainable rate as the network size grows. For example, the messaging complexity is only a function of the number of neighbours of each mobile. We have computed the average neighbour complexity above. The computational complexity is a function of the number of mobiles in the network, and grows as a linear function of the number of mobiles in the network. The protocol is adaptive. If a mobile leaves the network another mobile can be selected to be the CH. We envisage that the distance-based fairness would be well-suited to deployment in a Metropolitan or a Local Area Network where variations in mobile location relative to the BS could be exploited to increase the mobile sensing platform’s life-time. In this work we did not consider the energy consumption aspects of various mobile scan, idle mode, etc procedures. We will investigate how these processes may be optimized in future work.

VI. CONCLUSIONS

The limiting factor of mobile devices as a sensing platform is battery life. In this paper we investigated the fairness of existing CH election approaches, which penalize mobiles for being farther away from the BS. We proposed a distance-based fairness CH election protocol, which reduced the reporting load on mobiles which were far away from the BS by reducing the number of times they acted as CHs. Simulation results demonstrated that on average the difference in mobile battery life-times of the farthest away and closest mobiles could be reduced by approximately 66% which ensured that environment sensed by the mobiles was sensed for a longer period, with full sensing coverage, than before.

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