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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 burden placed on the battery of a mobile. Given that the power consumed by the receive circuitry of a mobile depends on the bit-size of a message, we exploit the potential to vary the transmit power to reduce energy consumption. The advantages of leveraging a hybrid architecture consisting of WiFi-Direct [9], WiFi or Bluetooth and 3G, to save network energy, have been examined in [10]. An Android prototype system evaluated in [4] motivated energy consumption initialization

parameters for the present paper. These works did not consider approaches for incorporating network management policies into these energy saving mechanisms. They concluded that using a hybrid architecture instead of a 3G approach facilitates at least a 50% energy saving; in these works the authors did not address how to select the CH. The high cost to a CH of such a scheme was highlighted. One open question that results from these works is that there is a need for CH election algorithms that expose a set of tuning functions to the network manager so that an array of policies can be chosen. Our main contribution is a method for promoting fair battery usage.

Contribution: The physical distribution of mobiles and the gateway cannot be controlled; however, the selection of CH can. We investigate two policies that promote fairness.

Policy 1: The elected CHs should change as a function of time to ensure that all costly transmissions are not borne by a single mobile. A secondary effect of this is that the average lifetime of all mobiles should be increased if they delegate cluster-headship. This functionality is achieved by LEACH in [5], which serves as our base-line comparison method.

Policy 2: If a mobile is closer to the gateway than many of the other cluster members, it may be desirable to increase the frequency that this mobile becomes a CH, as transmissions to the gateway may be cheaper for this mobile than for each of its peers. If fair battery usage is achieved it may also be useful to increase or decrease 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. 1 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

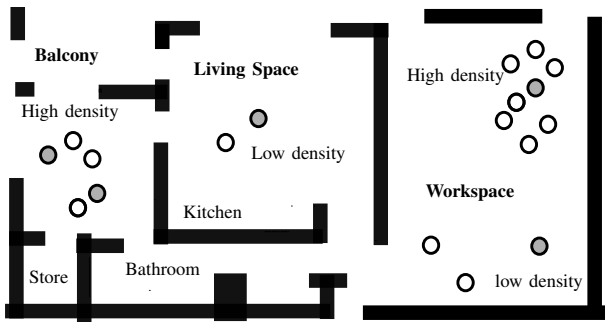


Fig. 1. Scenario: A portion of a university campus consisting of three primary zones is illustrated: a shared Work-space, Living space and Balcony area. The density of mobiles in each area may change in time and space and also their distance from the BS. A 3G BS is located 1km away from the front of the living area. Mobiles are denoted by circles. Cluster heads are grey, filled-in circles. We posit that the number of cluster heads and their identities should depend on the distance from the BS.

of mobiles in each area changes with time and space, a process which has been described previously using a Levy Walk [11]. 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.

III. POWER CONSUMPTION

In Fig. 1 data transmissions between mobiles are achieved by long-range wireless technologies, e.g. 3G, 4G, and short-range wireless technologies, WiFi, Bluetooth [15] and WiFi-Direct, which typically place a lower energy demand on the mobile [16]. We motivate our contribution using a simple linear array of mobiles in Fig. 2.

If there is a large distance between the mobiles and the Base Station (BS), the transmitter amplifier will require more energy for the signal to be received by the BS. In order to define the energy dissipated by the receiver a number of terms are introduced. The transmitter energy dissipated in the circuit is E_T in Joules (J). The receiver energy dissipated in the circuit is E_R J. The size of a message is k bits. The transmit distance

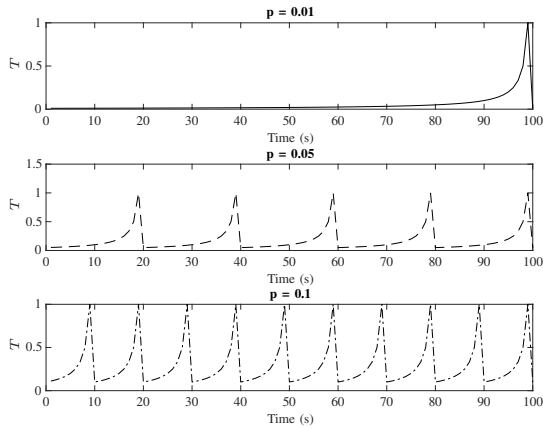


Fig. 4. The threshold is illustrated as a function of p . The threshold $T(t)$ is periodic; its period is set by p . For p small, the period is long; for p large the period short. Each epoch lasts 1 second in duration.

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,

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

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 $t = \hat{t}$

$$r(\hat{t}) = \int_0^{\hat{t}} s(t) dt. \quad (12)$$

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

$$T(t) = \frac{p}{1 - p \operatorname{mod}(r(t), \frac{1}{p})}, \quad (13)$$

where $\operatorname{mod}(r(t), \frac{1}{p})$ 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. 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

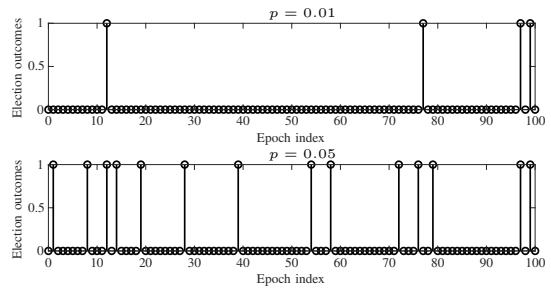


Fig. 5. Effect of p : Small values of p cause the inter-CH duration to be long in general. Large values of p causes this inter-CH duration to be decreased.

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

$$\alpha_a R(E_e + \epsilon a^2) > \alpha_b R(E_e + \epsilon b^2). \quad (14)$$

We relax the constraint that all mobiles have the same probability of being a CH. Instead, weights are introduced, α_a and α_b , for mobile a and b respectively. We assume that E_e '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 α_n for the n -th mobile to be

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

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 α_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 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 base-line 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 $0.001 \times 4 \times 60 \times 60 = 14.4\text{J}$. We use the constants $E_e = 50 \times 10^{-9}\text{J/b}$ and $\epsilon = 100 \times 10^{-12}\text{J/b/m}^2$ 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 life 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. $p = .01$, $.05$ 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, $e = p_1t + p_0$, 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 I 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

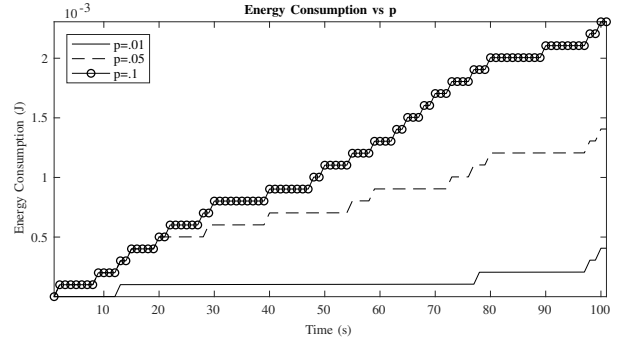


Fig. 6. Cumulative sum of the energy consumed transmitting 1 bit for $p = .1$, $.05$ and 0.01 . Direct transmissions to the BS consume significantly more than p2p communications. These time-series increase monotonically.

TABLE I
MOBILE LIFE-TIME GIVEN 1B AND 1KB TRANSMISSIONS AND THE AVERAGE NUMBER OF TIMES MOBILES ARE CHS.

	$p = 0.01$	$p = 0.05$	$p = 0.1$
$k = 1\text{bit}$	15400 days	5114 days	3409 days
$k = 1\text{kbit}$	15.4 days	5.114 days	3.409 days
CH	246	786	1206

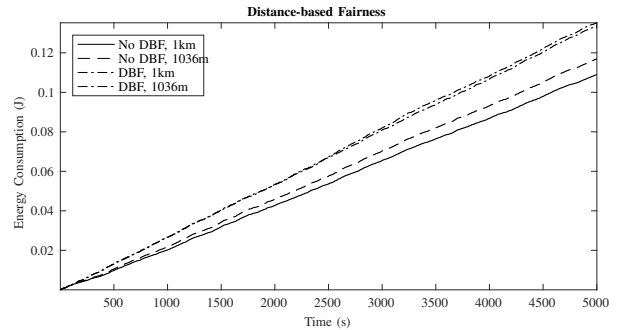


Fig. 7. When distance-based fairness is not used the lifetime of mobiles at different distances from the BS depends on this distance. As a consequence parts of the sensing topology may run out of battery before other parts. The battery life-time for both mobiles running distance-based fairness is approximately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

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 1k 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 a mobile depends on the distance of the mobile from the BS. When $p = .1$ both mobiles are CHs the same number of times ≈ 1000 times, however the mobile

TABLE II
DISTANCE-BASED FAIRNESS MOBILE STATISTICS WHEN $p = .7$, WHEN 1B IS TRANSMITTED.

	$d = 1\text{km}$	$d = 1036\text{m}$
Life-time (days)	2897	2804
CH count	1034	978

TABLE III
DISTANCE-BASED FAIRNESS VS BASE-LINE ($p = .1$) FOR $k = 1\text{B}$.
COLUMNS 2 AND 3 GIVE THE LIFE-TIME AND FREQUENCY OF CH-SHIP OF THE BASE-LINE METHOD. COLUMNS 4 AND 5 GIVE THE SAME STATISTICS FOR THE SAME MOBILES RUNNING DISTANCE-BASED FAIRNESS.

	$d = 1\text{km}$	$d = 1036\text{m}$	$d = 1\text{km}$	$d = 1036\text{m}$
Life-time (days)	3149	2935	2638	2563
CH count	1086	1086	1299	1246

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. 15. 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 distanced-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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