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LETTER

Optimal Number of Active Users for Minimizing Average Data Delivery Delay in People-Centric Urban Sensing

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SUMMARY We present a numerical analysis of the optimal number of active mobile users for minimizing average data delivery delay in intelligent people-centric urban sensing, in which context-aware mobile devices act as sensor-data carriers and sensor nodes act as data accumulators within CDMA cellular networks. In the analysis, we compute the optimal number of mobile users for different environmental conditions and then investigate the minimum average data delivery delay for this optimal number of mobile users.

key words: *urban sensing, minimum delay, optimal number of active users, sensor data, CDMA*

1. Introduction

Recently, many academic and industry projects have set out to implement people-centric urban sensing by utilizing mobile devices (MDs) such as mobile phones, personal digital assistants (PDAs), and smart phones for environmental data collection in daily urban lives [1]–[5]. These MDs have enough spare resources for processing and communication to be used as mobile gateways to collect sensor data and forward the data to a base station (BS).

Some additional applications for urban sensing have been introduced in the literature. Jian Ma et al. [6] presents the architecture of a mobile-enabled wireless sensor network (mWSN) to gather large-scale information via networked wireless sensors and mobile phones. Fei Hu et al. [7] and D. Malan et al. [8] present mobile telemedicine applications in which wireless sensors and MDs are used to monitor patients. In these applications, the sensor data can not be immediately transferred to the BS after being sensed but instead must be buffered at sensor nodes (SNs) until mobile collectors (i.e. MDs) approach. This means a longer delay in sensor-data delivery. Such delays can cause problems for patient-monitoring applications in particular, which require that sensor data be transmitted to the BS as quickly as possible to cope with an occasional emergency. Intuitively, as the number of MDs increases in the sensor field, the probability of an MD encountering an SN will also increase, decreasing data delay. On the other hand, an increase in the number of MDs within the CDMA cellular network may create a significant uplink data-transmission delay, due to the increased multi-user access interference (MAI), which limits the uplink capacity. Because the performance of the CDMA system is interference-limited rather than noise-limited, the effects of noise are negligible. The goal of this paper is to assign the optimal number of MDs to the sensor field so that sensor data are transferred as quickly as possible from SNs to the BS. We analyze the optimal number of active mobile users for minimizing average data-delivery delay using the tradeoff relation between encountering delay and uplink transmission delay.

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2. System Model

Suppose that the network is composed of N_m MDs and N_s energy-limited static SNs, which are deployed randomly (with a uniform distribution) in a two-dimensional square sensing field S of size $\|S\| = Z$. The MDs move randomly with a constant velocity in the sensing field.

As illustrated in Fig. 1, each MD serves as a bridge to the BS (i.e. eNodeB [9]), which can plug into a residential broadband connection to provide a mobile signal directly in the indoor environment. The BS can gather sensory information that can be stored and forwarded to the internet. The procedure of sensor-data delivery is as follows: Each SN captures and encodes relevant information from a designated area and holds the sensed data in the buffer until the MDs approach. Assuming the SN buffer can store more data without overflow, each SN transmits the sensed data through a single-hop to MDs when one SN encounters one MD. Each MD gathers sensor data from the sensor field, and then the MDs forward the composite bit stream to the BS.

3. Optimal Number of Active Users for Minimizing Average Data Delivery Delay

As shown in Fig. 2, sensor-data delivery delays in people-centric urban sensing are mainly divided into four ma-

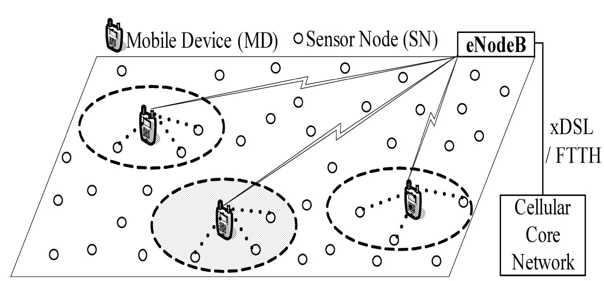

Fig. 1 A people-centric urban sensing for indoor monitoring.

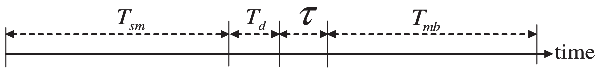

Fig. 2 Data delivery delay in people-centric urban sensing.

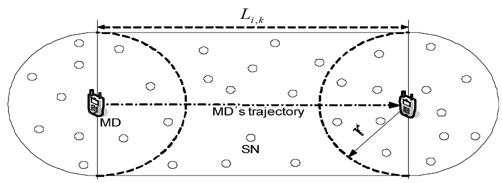

Fig. 3 Illustration of an cover area of k-th epoch for M_i.

jor components, T_{sm}, T_d, τ, and T_{mb}, where T_{sm} is average encountering delay between SN and MD; T_d is data-transmission time from SN to MD when the MD encounters the SN; τ is processing delay for generating sensor-data packets at the MD; and T_{mb} is the mean uplink data-transmission delay in the cellular network. Among them, T_{sm} and T_{mb} dominate the total sensor-data delivery delay from SN to BS, and their values are much larger than T_d and τ. Thus, T_d and τ are assumed to be negligible. Hereafter, T_t denotes the sum of T_{sm} and T_{mb}.

3.1 Average Encountering Delay (T_{sm})

Due to the mobility of MDs, sensor-data transmission occurs only when one SN has an encounter with one MD. Suppose that both MDs and SNs have same sensing range, r. The "Random direction mobility model" [6], [10] is used for the mobility pattern of the mobile devices, $M_i (i = 1 \cdots N_m)$. The mobility model is epoch-based, so the trajectory of MDs is a sequence of epochs. MDs move during each epoch with a constant velocity υ, and the moving direction of M_i is uniform and independent of its position. Each epoch duration of M_i is E_i, which can be expressed as the time interval between M_i's starting and end points; $E_i (i = 1 \cdots N_m)$ are independent and identically-distributed(iid) exponential random variables with mean $\overline{E}$. Depending on the E_i, the distance of different L_is are also iid random variables with average distance of an epoch $\overline{L} = \upsilon \times \overline{E}$.

Assuming a stationary distribution of MDs, independent MDs approach a certain static SN from different directions with equal probability. In particular, one mobile device M_i encounters one static SN and covers the SN during an epoch. Since an area of size $\pi r^2 + 2rL_{i,k}$ is covered by M_i during the k_{th} epoch as illustrated in Fig. 3, the number of necessary epochs Y_i until the first SN-MD encounter is geometrically distributed with averaged $\frac{1}{p} = \frac{Z}{\pi r^2 + 2r\overline{L}}$ [6], [10]. Therefore, the number of necessary epochs Y must be the minimum of all $Y_i (i = 1 \cdots N_m)$, with the cumulative distribution function as

$$F_Y(y) = 1 - [1 - F_{Y_i}(y)]^{N_m} \tag{1}$$

Let $\overline{Y}$ be the average of number of epochs; then the expected mean encountering delay between SN and MD can be calculated as

$$T_{sm} = E[T_{sm}] = \frac{\overline{Y} \times \overline{L}}{\upsilon} \tag{2}$$

3.2 Mean Uplink Data Transmission Delay (T_{mb})

We assume that the uplink channel is a slowly varying flat Rayleigh fading channel CDMA uplink cellular networks; if so, the channel is slow enough that the channel gain remains unchanged during a successful packet transmission. Moreover, the uplink channel gain, transmission power, and data rate are unchanged during the retransmission for a successful packet transmission. Utilizing optimal power/rate control for a given mean transmission power [11], the minimum mean delay under joint power (P_t^*) and rate (R^*) is derived as

$$T_{mb}(P_t^*, R^*) = \frac{DN_t\left(\overline{\sqrt{1/G}}\right)^2 \gamma_0^*}{\overline{P}_t\left(1 - \alpha e^{-\beta\gamma_0^*}\right)^D} \tag{3}$$

where the optimum required signal-to-interference ratio (SIR) is

$$\gamma_0^* = -\frac{lambertw\left(-1, -\frac{\exp(-1/D)}{\alpha D}\right) + \frac{1}{D}}{\beta}$$

where α and β describe various types of modulation. For instance, binary phase shift keying (BPSK) modulation is expressed by $\alpha = 0.5$ and $\beta = 1$. $\overline{P}_t$ is the average transmission power P_t, which can be controlled by the channel gain G. D is the number of symbols per packet, and $lambertw(.)$ denotes the Lambert W-function. In addition, $\overline{C}$ is the average number of SNs within the average length of an epoch, which can be expressed by the sensor node density

$$\bar{C} = \rho * \left(\pi r^2 + 2r\bar{L}\right) = \frac{N_s}{Z} \cdot \left(\pi r^2 + 2r\bar{L}\right) \tag{4}$$

where ρ is the sensor node density equal to $\frac{N_s}{Z}$ in the area of Z. ϕ_a is the amount of data collection from SNs during the average epoch, which is described by

$$\phi_a = \phi_c * \bar{C} \tag{5}$$

where ϕ_c is a fixed-packet length of sensor-data from one SN to one MD. Since MAI dominates the background, N_t is the total interference (i.e. intra-cell MAI) ignoring background noise. For simplicity, we assume that the received signals from all mobile users at the BS have equal power through perfect power control; $\overline{P}_t$ always satisfies the same receiver power according to the number of active mobile users. The signal energy-to-interference spectral density ratio, E_b/N_t of a MD can be described by

$$\frac{E_b}{N_t} = \frac{S/R}{I/W} = \frac{P_r}{(N_m - 1)P_r} \cdot \frac{W}{R} = \frac{W}{(N_m - 1)R} \tag{6}$$

where S = received signal power; I = interference power;

R = data rate; W = spreading bandwidth (or chip rate); and P_r = constant received power from a MD. From (6), the $\frac{\bar{P_t}}{N_t}$ is derived as

$$\frac{\bar{P_t}}{N_t} = R \cdot \frac{E_b}{N_t} = \frac{W}{N_m - 1} \tag{7}$$

Using (4) and (7), $T_{mb}(P_t^*, R^*)$ in (3) is represented by

$$T_{mb}(P^*, R^*) = \frac{\phi_a (N_m - 1)\left(\overline{\sqrt{1/G}}\right)^2 \gamma_0^*}{KW(1 - \alpha e^{-\beta \gamma_0^*})^{\phi_a}} \tag{8}$$

where the optimum required SIR is

$$\gamma_0^* = -\frac{lambertw\left(-1, -\frac{K \exp(-K/\phi_a)}{\alpha \phi_a}\right) + \frac{K}{\phi_a}}{\beta}$$

where K denotes the constellation size of different modulation levels.

3.3 Min.Delay (T_t) with Optimal Number of Active Users

From (2) and (8), as the number of active mobile users (N_m) increases, T_{sm} decreases, while T_{mb} increases. We are suppose to find minimum value of the function: $T_t(N_m) = T_{sm}(N_m) + T_{mb}(N_m)$ for $T_{sm}(N_m) > 0$, $T_{mb}(N_m) > 0$. Applying the arithmetic and geometric mean inequality, we have:

$$\frac{T_{sm}(N_m) + T_{mb}(N_m)}{2} \geq \sqrt{T_{sm}(N_m) T_{mb}(N_m)} \tag{9}$$

Further, the equality holds if and only if $T_{sm}(N_m) = T_{mb}(N_m)$. In other words, the equality holds when intersection points exist between $T_{sm}(N_m)$ and $T_{mb}(N_m)$ as the number of active users increased. The minimum $T_t(N_m)$ can be calculated as $2\sqrt{T_{sm}(N_m) T_{mb}(N_m)}$, and then the optimal number of active mobile users for minimum delay can also be derived. In the case of a multi-cell system, it is easy for us to expand our analysis for a given frequency reuse factor. Due to space limitations, we have considered only a single cell.

4. Simulation Results

We assume that a large number of SNs are deployed in the cell area $Z = 2500$. Only one MD can be used for each active user. Each MD moves with general pedestrian walking speed range ($\upsilon = 4 \sim 6$ km/h) to guarantee a sufficiently long session to successfully gather the potential sensor data from underlying SNs. If the MDs move too quickly, the MD does not have enough time to exchange control packets or data packets with SNs. Every SN in the field always has stored sensor data to transmit. The mobility pattern of MDs is according to an epoch-based random-direction mobility model with a constant velocity in the cell. Each MD experiences lognormal shadowing as in [11] and the channel gain G is given as $G = 10^{\frac{\delta}{10}}$, where δ is the attenuation in decibels due to shadowing and follows a Gaussian distribution with a zero mean and standard deviation σ as $p_\delta(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{x^2}{2\sigma^2}\right)$. Assuming that a stop-and-wait automatic request control and BPSK modulation are used for uplink data transmission from MDs to BS, ϕ_c is equal to 250 bits, W is 3.84 Mcps, and $\sigma = 12$.

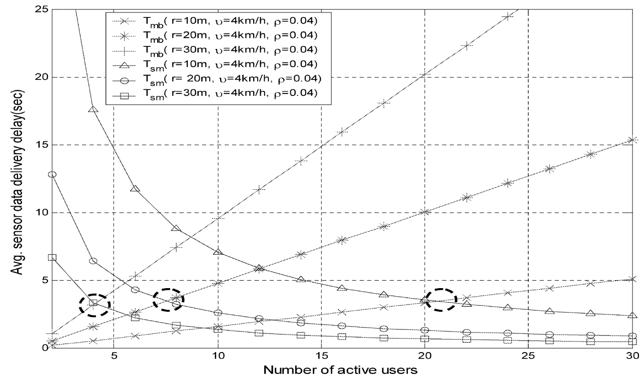

Fig. 4 N_m^* at intersection points between T_{sm} line and T_{mb} line when $r = 10\,\mathrm{m} \sim 30\,\mathrm{m}$, $\rho = 0.04$, $\upsilon = 4$ km/h.

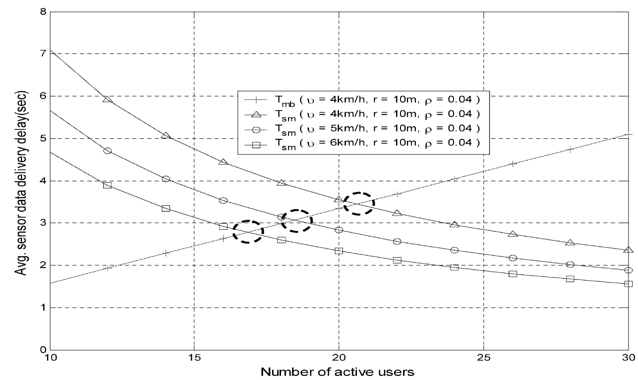

Fig. 5 N_m^* at intersection points between T_{sm} line and T_{mb} line when $\upsilon = 4 \sim 6$ km/h, $\rho = 0.04$, $r = 10$ m.

Figure 4 shows the tradeoff between T_{sm} and T_{mb} when the number of MDs increases. Furthermore, as the sensing range increases, the value of T_{sm} decreases, because a single MD can cover a large number of SNs at once in each epoch; in this case, the MD has a relative high probability of encountering a certain SN even if the MD moves slowly. On the other hand, the value of T_{mb} increases, because the amount of sensor data to upload increases according to the number of SNs in each epoch. Utilizing Eq. (9), the optimal number of active users for minimum delay can be obtained from the intersection points where T_{sm} and T_{mb} have the same values as constants υ and ρ.

Figure 5 also shows the tradeoff between T_{sm} and T_{mb} under different υ with the constant r, ρ, and $\overline{L}$. As the υ increases, the T_{sm} is decreased, because MDs move with high velocity and thus can encounter SNs quickly. However, utilizing (4) and (5), the T_{mb} remains unchanged when the υ increases because the total amount of uplink data from SNs within the coverage area of $\pi r^2 + 2r\overline{L}$ for a given average distance $\overline{L}$ is constant due to a fixed $\overline{L}$. Consequently, there

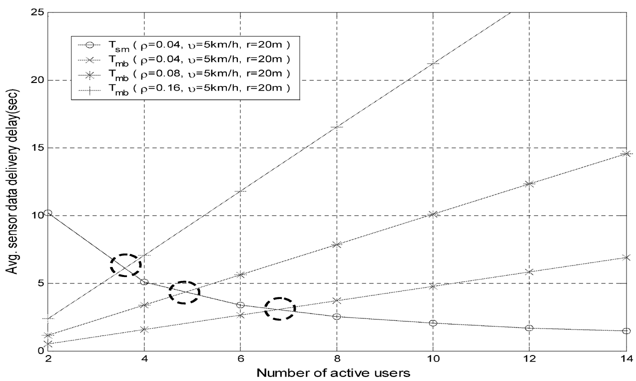

Fig. 6 N_s^* at intersection points between T_{sm} line and T_{mb} line when $\rho = 0.04, 0.08, 0.16$, $\upsilon = 5\,\text{km/h}$, $r = 20\,\text{m}$.

Table 1 Optimal number of active users vs. Min. delay under different conditions.

Parameters			N_m^*			$T_t = Min.(T_{sm} + T_{mb})$		
υ (km/h)	r (m)	ρ	N_m^*	$\lceil N_m^* \rceil$	$\lfloor N_m^* \rfloor$	T_t (sec)	$\lceil T_t \rceil$ (sec)	$\lfloor T_t \rfloor$ (sec)
4	10	0.04	20.5	21	20	5.2425	5.2396	5.2363
4	20	0.04	7.52	8	7	5.2431	5.2353	5.2614
4	30	0.04	4.09	5	4	5.1326	5.2734	5.1238
4	10	0.04	20.5	21	20	5.2425	5.2396	5.2363
5	10	0.04	18.5	19	18	4.9438	4.9472	4.9425
6	10	0.04	16.8	17	16	4.7155	4.7147	4.7142
5	20	0.04	3.6	4	3	5.3067	5.1705	5.605
5	20	0.08	4.89	5	4	5.8367	5.8477	5.8141
5	20	0.16	6.78	7	6	8.1562	8.2583	7.792

are three intersection points.

Figure 6 shows the minimum delay under different ρ with a fixed υ, r, and $\overline{L}$. If the total number of SNs (N_s) in the square area (Z) is equal to 100, then $\rho = 100/2500 = 0.04$. We compared the results when the N_s is equal to 100, 200, and 400. As the value of ρ increases, the number of SNs in the coverage area of $\pi r^2 + 2r\overline{L}$ for a given average distance $\overline{L}$ increases. From (4) and (5), the amount uplink data from underlying SNs is increased when the ρ increases. On the other hand, T_{sm} remains unchanged when the ρ increases because T_{sm} is irrelevant to ρ as shown in (2).

According to the results of Fig. 4, Fig. 5, and Fig. 6, Table 1 shows the obtained optimal number of active users and the minimum delay for each set of cases for various given conditions. There are two different values: theoretical optimal values (N_m^*) vs. real values ($\lceil N_m^* \rceil$ or $\lfloor N_m^* \rfloor$). Because the number of active users must be an integer value in the real system, the integer value is defined as the real value. From Table 1, we can observe that the real values of the optimal number of active users approximate the theoretical values rounded off to the nearest integer.

5. Conclusion

This paper presents the optimal number of active users for minimizing the delay of people-centric urban sensing under various given conditions. The results show a tradeoff between the CDMA uplink data-transmission delay and the encountering delay between MDs and SNs. We also compute minimum average sensor-data delivery delay under the optimal number of active users in order to put the theoretical values into practice. Based on this work, we will attempt to determine which N_m^* is appropriate for practical environment for different υ, r and ρ values.

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