A Trade-off between Energy Consumption Reduction and Responsiveness in Information Delivery for Delay-Tolerant Sensor Networks with Mobile Sink

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ABSTRACT
In a delay-tolerant sensor network where the sink is mobile, a node can conveniently hold an information packet until the sink comes closer. This allows to both decrease the number of wireless hops required to deliver the information to the sink and reduce energy consumption. Thus, mobility of nodes can be exploited to increase energy efficiency in sensor networks. However, a major drawback of the above policy is that it causes delay which may be not acceptable for the application. In this paper a trade-off between energy efficiency and delay is investigated. More specifically, an analytical framework which allows to evaluate the expected delivery cost with respect to the maximum delay acceptable for the application is derived and assessed by comparison with simulation results. Numerical results show that the analytical framework is very accurate and, as expected, accuracy increases as the density of nodes in the network increases.

Categories and Subject Descriptors
C.2.1 [Computer-communication networks]: Network Architecture and Design—Wireless communication

General Terms
Performance

Keywords
Energy consumption, responsiveness, sensor networks

1. INTRODUCTION
Mobility of nodes can be exploited to increase energy efficiency in mobile networks. More specifically, the idea of exploiting mobility of nodes for information delivery in case of delay-tolerant applications has been recently proposed in the literature [2]. Data is sent when either source and destination become close to each other or a relay node is given the data when it is close to the source and thus can deliver data to the destination once it becomes close to it. In this way, the number of wireless hops needed to deliver a packet decreases as well as the overall energy consumption; moreover, also the overall network capacity (i.e. the number of packets that can be delivered to the destination in the unit of time) increases. This is intuitive and was theorized for the first time in [4] for an ad hoc network scenario. Lately, several approaches have been proposed which exploit such an idea.

As an example, Message Ferrying (MF) [13, 14], is a proactive mobility-assisted approach proposed for ad hoc network scenarios which utilizes a set of special mobile nodes, called message ferries, to provide communication services for nodes in the network. Message ferries move around the deployment area according to a given, well known trajectory and take responsibility for carrying data between nodes.

In [6] a proactive scheme that modifies the trajectory of mobile nodes in ad hoc networks is proposed. This mechanism allows to guarantee that messages are delivered as fast as possible and network connectivity is maximized. Other similar solutions rely on Epidemic Routing [5, 10]. Obviously, mobility can be exploited to improve performance in sensor network scenarios as well. Here, networks are composed of tiny and battery powered devices. Reducing energy consumption is thus a major concern since it can allow an increase in network lifetime. Therefore, mobility should be exploited to decrease energy consumption. This is the rationale behind the DataMule concept [9]. Mobile entities (called MULEs) pick up data from sensors when in close range, store it, and drop it to wired access points. Therefore, DataMules achieve energy efficiency in sensor networks by using short-range transmissions. The trajectory of the MULE may be either random or driven by the collected data, and thus, not known in advance by all nodes. However, this kind of policies may introduce very long delays that are not even acceptable for certain delay-tolerant applications, and therefore appropriate trade-offs are needed. In this paper we study the above trade-offs analytically. The scenario considered in our work is a sensor network composed of static devices disseminated over the sensed area. Sensor nodes monitor the parameters required by the appli-
cation, and need to deliver this information to a sink moving within the sensed area in a time interval no longer than a maximum value, $\Delta_M$. The corresponding communication is usually performed via wireless multihopping. Our work relies on the following assumptions:

- All nodes know the trajectory of the mobile sink. This is a common assumption in the literature [13, 14] and can be achieved in several ways, e.g., by periodically flooding the network with information about the sink trajectory or pre-establishing a trajectory during the set-up phase and communicating this information to the network nodes only once during set-up.

- The delay introduced by the multi-hop communications, such as transmission delay, propagation delay, and queuing delay is negligible if compared to the time interval needed for the mobile sink to come close enough to the information source.

- A geographical forwarding protocol is available which allows to choose, at each hop, the next relay closest to the destination. To this aim, several protocols have been proposed in the literature, e.g., [11, 12, 3].

In this paper we derive an analytical framework which allows to evaluate the expected delivery cost corresponding to the maximum delay acceptable for the application. Accuracy of the analytical framework is assessed by comparison with simulation results. Numerical results show that the analytical framework is very accurate and, as expected, accuracy increases as the density of nodes in the network increases.

The rest of this paper is organized as follows. In Section 2 we describe the system model and introduce the analytical framework. Numerical examples are shown in Section 3 and concluding remarks are drawn in Section 4.

2. ANALYTICAL FRAMEWORK

Objective of our study is the evaluation of a trade-off between delay and energy efficiency in delay-tolerant applications. This can be particularly useful in case of wireless sensor networks with one or more mobile sinks. In fact, if the mobile sink moves, a node may decide to hold the information until the sink becomes closer, thus decreasing energy consumption.

This is a trade-off problem and, thus, an analytical framework which allows to calculate the expected delivery cost, given a threshold on the maximum tolerable delay, $\Delta_M$, is required.

Accordingly, in Section 2.1 we characterize the system and introduce some notation; then, in Section 2.2, we evaluate the expected delivery cost as a function of a threshold on the maximum tolerable delivery delay, $\Delta_M$.

2.1 System Model

Assume that $N$ nodes and one mobile sink are deployed in a given sensed area.

An appropriate reference system can be introduced which allows to express any possible location within the sensed area through a 2-ple $(x,y)$. Accordingly, at any time instant, $t$,

\[ \mathbf{p}_i(t) = (x_i(t), y_i(t)) \quad \text{with } i \in [0,N] \]  

where $(x_i(t), y_i(t))$ represent the coordinates of node $i$ at time $t$. For simplicity, in the following, we will use $i = 0$ to indicate the mobile sink.

Accordingly, the distance between two nodes $i$ and $j$ at time $t$, $d_{i,j}(t)$, can be calculated as follows:

\[ d_{i,j}(t) = \| \mathbf{p}_i(t) - \mathbf{p}_j(t) \| = \sqrt{(x_i(t) - x_j(t))^2 + (y_i(t) - y_j(t))^2} \quad \forall i,j \in [0,N] \]  

Moreover, we assume that all nodes, except for the mobile sink, are static, i.e.,

\[ \mathbf{p}_i(t) = (x_i,y_i) \quad i \in [1,N] \text{ and } t \geq 0 \]  

Observe that our framework can be easily extended to the 3-dimension space representation and to a multi-sink scenario.

The position of the generic $i$-th node can be represented by a position vector

\[ \mathbf{p}_i(t) = (x_i(t), y_i(t)) \quad \text{with } i \in [0,N] \]  

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We assume that all nodes, except for the mobile sink, are static, i.e.,

\[ \mathbf{p}_i(t) = (x_i,y_i) \quad i \in [1,N] \text{ and } t \geq 0 \]  

Moreover, we assume that each node knows its own position as well as the mobile sink position. To this purpose, GPS or GPS-less techniques [1] can be exploited. Assuming that the mobile sink moves around the sensed area and nodes know its trajectory, for any time instant $t$, any node, $i$, can evaluate its distance from the sink, $d_{i,0}(t)$.

In Figure 1 an illustrative example is shown. We consider a squared sensed area of size $400 \times 400$ m$^2$ as shown in Figure 1 (a). The mobile sink moves in this area according to a trajectory represented by the dashed line in figure. The position vectors of the mobile sink, $\mathbf{p}_0(t)$, are shown for two different values of the time instant $t_1$ and $t_2$. We also represented the position of a certain sensor node $S$ and its trajectory. For simplicity, in the following, we will use $i \in [0,N]$ and $t \geq 0$.

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For any 2-ple of time instants $t_1$ and $t_2$, with $t_1 < t_2$, we denote as $d_{i,0}^{\text{min}}(t_1,t_2)$ the minimum distance between the node $i$ and the mobile sink in the time interval $[t_1,t_2]$, i.e.,

\[ d_{i,0}^{\text{min}}(t_1,t_2) = \min_{t_1 \leq t \leq t_2} \{ d_{i,0}(t) \} \]

and as $\tau_i^{\text{min}}(t_1,t_2)$ the time instant when the minimum distance is reached for the first time in $[t_1,t_2]$, i.e.,

\[ \tau_i^{\text{min}}(t_1,t_2) = \{ t^* : d_{i,0}(t^*) < d_{i,0}(t), \forall t \in [t_1,t^*] \text{ and } d_{i,0}(t^*) < d_{i,0}(t), \forall t \in [t^*,t_2] \} \]

Suppose that at time $t = 0$ a given node $i$ receives from the application a new information packet which must be delivered to the mobile sink and that, based on the application requirements, the information must reach the sink within a time interval $\Delta_M$. It is obvious that the node can save energy by storing the packet in a local buffer until time $\tau_i^{\text{min}}(0, \Delta_M)$, and routing the packet towards the point characterized by the position vector $\mathbf{p}_0(\tau_i^{\text{min}}(0, \Delta_M))$.

This is shown in Figure 1 (c) where we represent the average power consumption due to the transfer of a packet from $\mathbf{p}_S$ to $\mathbf{p}_0(t)$ vs. time $t$. The data represented in Figure 1 (c) has been obtained through simulation considering $N = 100$ nodes Poisson-distributed in the sensed area shown in Figure 1 (a). To derive this figure we assumed that the power consumption for a single packet transmission is equal to $4 \mu$W which corresponds to a coverage radius of 75 m [15]. By comparing Figure 1 (b) and Figure 1 (c) we observe that, as expected, the power consumption decreases...
when \( d_{S,0}(t) \) decreases and viceversa. This confirms that, in order to preserve energy efficiency, data packets should be routed at time \( \tau_{\min}(0, \Delta_M) \to \) towards \( p_0(\tau_{\min}(0, \Delta_M)) \).

## 2.2 Delivery cost

Let us denote \( C(d) \) the expected cost in terms of power consumption required to route an information packet between two points whose distance is \( d \). According to what we said in the previous section, the delivery cost we must evaluate is \( C( d_{\min}(0, \Delta_M) ) \).

In this section we calculate this cost function \( C(d) \) as follows:

\[
C(d) = \begin{cases} 
  P + C(d - \overline{G}(d)) & d > R \\ 
  P & d \leq R 
\end{cases}
\]  

(6)

where

- \( P \) is the power consumed to transmit and receive a packet;
- \( R \) is the radio coverage of the current relay node;
- \( \overline{G}(d) \) is the expected one-hop progress towards the destination distant \( d \). To better explain the concept of progress [8], let us consider the scenario in Figure 2. A certain node \( S \) has a packet to transmit to the destination \( D \) whose distance from node \( S \) is \( d \). Suppose that in the radio coverage range of \( S \) the more convenient next relay (i.e. the node closest to \( D \)) to forward a packet towards \( D \) is node \( M \), whose distance from the destination is \( d' \). If this is the case, the progress towards the destination is given by \( (d - d') \).

Accordingly, \( \overline{G}(d) \) is the expected value of \( (d - d') \).

In the following we denote \( G(d) \) the random variable representing the progress towards the destination achieved in one hop when the destination has a distance \( d \) from the current relay node, \( S \).

Obviously, \( \overline{G}(d) \) can be computed as:

\[
\overline{G}(d) = E \{ G(d) \} = \int_{-\infty}^{+\infty} x \cdot f_{G(d)}(x) dx 
\]  

(7)

where \( f_{G(d)}(x) \) represents the probability density function of the random variable \( G(d) \).

The function \( f_{G(d)}(x) \) can be calculated as the derivative of the corresponding probability distribution function \( F_{G(d)}(x) \) which is defined as follows:

\[
F_{G(d)}(x) = \Pr \{ G(d) \leq x \} 
\]  

(8)

being \( 0 \leq x < R \).

The probability in the right hand side of eq. (8) is equal to the probability that the node within the coverage area of \( S \), which is the closest to the destination \( D \), is distant from \( D \) at least \( (d-x) \). This means there should be no nodes in the grey area shown in Figure 2 and called \( a(d-x,d) \), representing the area of intersection between two circles, namely the one centered in \( S \) and having radius equal to \( R \) and the other centered in \( D \) with radius equal to \( (d-x) \) and \( 0 \leq x < R \).

If we assume that nodes are Poisson-distributed in the sensed area with density \( \lambda = N/A \), where \( A \) represents the area of the entire sensed region, it follows that the probabil-
ity distribution function in eq. (8) can be calculated as

$$F_{G(d)}(x) = \begin{cases} 
0 & x < 0 \\
e^{-\lambda a(d-x,d)} & 0 \leq x < R \\
1 & x \geq R
\end{cases}$$

(9)

Accordingly, eq. (7) can be rewritten as follows:

$$E\{G(d)\} = \int_{-\infty}^{+\infty} x \cdot f_{G(d)}(x)dx$$

$$= [x \cdot F_{G(d)}(x)]_0^R - \int_0^R F_{G(d)}(x)dx$$

(10)

$$= R - \int_0^R F_{G(d)}(x)dx$$

In order to solve eq. (10) we need to calculate the area

$$a(d-x,d).$$

For sake of simplicity, we define

$$r = d - x.$$ Accordingly:

$$a(r, d) = \Psi + \Omega - \Phi$$

(11)

where \(\Psi, \Omega, \) and \(\Phi\) can be calculated applying Euclidean geometry. More specifically:

- Once we define \(\gamma(r)\) as follows:

$$\gamma(r) = 2 \cdot \text{arccos} \left( \frac{-r^2 + d^2 + R^2}{2 \cdot R \cdot d} \right)$$

(12)

the value of \(\Psi\) can be calculated as

$$\Psi = \frac{1}{2} \cdot R^2 \cdot \gamma(r)$$

(13)

- Once we define \(\theta(r)\) as follows:

$$\theta(r) = 2 \cdot \text{arccos} \left( \frac{r^2 + d^2 - R^2}{2 \cdot r \cdot d} \right)$$

(14)

the value of \(\Omega\) can be calculated as

$$\Omega = \frac{1}{2} \cdot \theta(r) \cdot r^2$$

(15)

- Finally, \(\Phi\) can be calculated as

$$\Phi = 2 \cdot \sqrt{s \cdot (d-R) \cdot (s-r) \cdot (s-d)}$$

(16)

where \(s\) is given by

$$s = (R + r + d)/2$$

(17)

The geometrical meaning of \(\Psi, \Omega, \) and \(\Phi\) can be clarified looking at Figure 2. In this figure \(\Psi\) is the circular sector SAB, \(\Omega\) is the circular sector DAB and \(\Phi\) is the polygon SADB.

Now we can evaluate the expected one-hop progress \(E\{G(d)\}\) as given in eq. (10) where the integral in the right hand side can be easily calculated numerically.

3. CASE STUDIES

In this section we apply the methodology described in Section 2 and assess the framework accuracy through comparison with simulation results. More in detail, in Section 3.1 we describe the simulation scenario, in Section 3.2 we apply the proposed methodology and in Section 3.3 we assess its accuracy.

3.1 Simulation scenario description

We considered a squared area of size 400 x 400 m² as shown in Figure 3. The mobile sink moves according to a periodic linear trajectory whose expression is \(y = x/2\) with velocity equal to \(v = 20\ \text{m/s}\. Therefore, the trajectory length is \(L = 447\ \text{m}\) and it is run by the mobile sink in a time interval equal to \(T = L/v\. Accordingly, if the position of the mobile sink is \((0, 0)\) at time \(t_0\), at time \((t_0 + T)\) the mobile sink location will be \((400, 200)\). At that time instant the mobile sink will move back to position \((0, 0)\) where it will arrive at time \((t_0 + 2 \cdot T)\). In this scenario, we will consider that the source of information, node \(S\), is located at position \(\overrightarrow{p_S} = (200, 200)\) as shown in Figure 3.

3.2 Numerical results

Let us suppose that at time \(t = 0\) node \(S\) has a new information packet to deliver to the mobile sink which is located in position \((0, 0)\), i.e., \(\overrightarrow{p_0}(0) = (0, 0)\). Accordingly, the distance between node \(S\) and the mobile sink varies as shown in Figure 4. The minimum distance between node \(S\) and the mobile sink is equal to \(d_{S}^{\text{min}}\) and is reached at time \(r_{\text{min}}\). In Section 2.1 we have pointed out that, in order to maximize the energy efficiency, information has to be delivered to the mobile sink when its distance from node \(S\) is \(d_S^{\text{min}}(0, \Delta M)\), defined as in eq. (4). In Figures 4 and 5 we show \(d_S\) vs. time \(t\) and \(d_{S}^{\text{min}}(0, \Delta M)\) vs. \(\Delta M\) respectively.

![Figure 3: Mobile sink trajectory in the considered area.](image)

![Figure 4: Distance between source node and mobile sink vs. time.](image)

Obviously, the following relationship holds

$$\begin{cases} 
\tau_S^{\text{min}}(0, \Delta M) > d_{S}^{\text{min}} = 89.46\ \text{m} & \text{if } \Delta M < \tau_S^{\text{min}} = 11.91 \ \text{s} \\
\tau_S^{\text{min}}(0, \Delta M) = d_{S}^{\text{min}} = 89.46\ \text{m} & \text{if } \Delta M \geq \tau_S^{\text{min}} = 11.91 \ \text{s}
\end{cases}$$

(18)
Figure 5: Minimum distance between source node and mobile sink vs. maximum delay.

The corresponding values of the delivery cost function, \( C(d_{min}^S(0, \Delta_M)) \), can be derived as given in eq. (6), once the expected one-hop progress, \( \bar{G}(d) \), has been calculated using eq. (10). In Figure 6 we show \( \bar{G}(d) \) vs. the distance \( d \), for different values of the number of network nodes, \( N \). The curves in Figure 6 have been obtained assuming that the radio coverage is \( R = 75 \) m.

Note that in Figure 6 the expected one-hop progress \( \bar{G}(d) \) increases as the distance \( d \) increases because the advantage of using intermediate relays increases as well. This is shown in Figure 7. Here two cases are considered; in the first one the source is \( S \), the destination is \( D_1 \), and the best relay is \( M \). In the second case, the source and the best relay remain the same, i.e., \( S \) and \( M \), but the destination is now \( D_2 \) which is farther away from \( S \) than \( D_1 \). Figure 7 shows that in the second case (dotted line) the progress towards the destination, \( \bar{G}(d) \), is higher than in the first case.

Figure 6: Expected progress towards the destination vs. the distance for different values of the node density.

The values of \( \bar{G}(d) \) represented in Figure 6 have been used to calculate the delivery cost function which is shown in Figures 8(a) and 8(b) vs. the maximum acceptable delay \( \Delta_M \), for different values of the number of nodes, \( N \), and the coverage radius, \( R \), respectively. In Figures 8(a) and 8(b) we have assumed that the transmission/reception power \( P \) used in eq. (6) is 4 \( \mu \)W, which is the power utilized by Crossbow MICAZ commercial sensor devices [15].

Observe that the delivery cost function has a stepwise behavior. The reason is that, given a certain value of the maximum acceptable delay \( \Delta_M \), we obtain a corresponding value of the minimum distance between the source and the mobile sink \( d_{min}^S(0, \Delta_M) \). Small decreases in \( \Delta_M \) cause small increases in the distance \( d_{min}^S(0, \Delta_M) \) which do not require a further hop and thus, the delivery cost function remains almost constant.

Increase in node density causes a reduction in the cost because more nodes closer to the destination are available for forwarding data packets. As expected, also an increase in the coverage radius causes a reduction in the cost because the probability of finding more nodes closer to the destination increases.

3.3 Accuracy Assessment

In order to assess the accuracy of the proposed methodology we compared the numerical results obtained with analysis to those obtained through simulation.

In Figure 9 we compare the expected values of the cost function obtained through our analysis to the values of the delivery cost obtained through simulation vs. the maximum acceptable delivery delay, \( \Delta_M \). In these figures we have considered different values of the number of nodes, \( N \), i.e. \( N = 500 \) and \( N = 1000 \) nodes. The positions of the \( N \) nodes have been generated according to a Poisson distribution in the sensed area.

The values shown in Figure 9 have been obtained averaging the values over 100 simulations. Observe that as \( \Delta_M \) increases, the delivery cost obtained through analysis exhibits a stepwise behavior as already discussed in Figures 8(a) and 8(b).

In all cases the delivery cost function calculated as given in eq. (6) is a good approximation of the delivery cost calculated through simulation. Also note that the accuracy increases as the number of nodes, \( N \), increases.

4. CONCLUSION

In this paper we have derived an analytical framework for the calculation of the optimal trade-off between energy efficiency and delivery delay in sensor networks with mobile sink.

More specifically, we derived an analytical framework which allows to evaluate the estimated delivery cost related to the maximum delay acceptable for the application. We used this framework in a relevant case study and evaluated the
effects of several parameters on the trade-off between energy efficiency and delay.

Accuracy of the proposed framework has been assessed through comparison with simulation results.

5. REFERENCES


