QoS-Aware Data Transmission and Wireless Energy Transfer: Performance Modeling and Optimization

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***Abstract*—With wireless energy transfer, a mobile node can operate perpetually without having a wired connection to charge its battery. In this paper, we present a quality of service (QoS) aware data transmission and wireless energy transfer for the mobile node. The node can request for wireless energy transfer or transmit a packet when the node is in a coverage area of an access point. The node supports service differentiation for different type of traffic (i.e., low and high priority data). To meet the QoS requirement of each traffic type, we present the performance modeling and optimization framework. The objective is to maximize the throughput, while the packet loss probabilities are maintained below the target levels. The optimal policy for the node is obtained from solving the constrained Markov decision process (CMDP). In addition, we present an application of the framework to a data mule for collecting, carrying, and transmitting data from sensors to the access point.**

***Index Terms*—Wireless energy transfer, mobile node, Markov decision process**

I. INTRODUCTION

After the remarkable invention of the coupled magnetic resonance by Kurs *et al.* [1], wireless energy transfer has become a promising solution to perpetuate an operation of wireless networks with mobile nodes. There is no need for the mobile node to have a wired connection to recharge its battery any more. A few works studied different issues of wireless energy transfer. [2] introduced a mobile unit which can be wirelessly charged and move to collect data from and supply energy to sensor nodes. [3] considered an optimization model of such a mobile unit. The objective is to maximize the ratio of vacant time of the mobile charging unit over the cycle time. [4] analyzed the impact of mobility of the mobile unit to the network performance. The realistic mobility models for the mobile unit was also introduced. [5] introduced a general MAC protocol to support wireless energy transfer and data transmission. [6] analyzed a two-node relay network with wireless energy transfer and multiple access. Multihop networking with wireless energy transfer was considered and analyzed (e.g., with energy routing protocol) in [7] and [8]. A stochastic optimization tool (i.e., Markov decision process) was adopted to find the optimal data transmission policy with wireless energy transfer [9], [10]. However, none of the works in the literature considered the quality of service (QoS) support and service differentiation.

In this paper, we consider the QoS-aware data transmission and wireless energy transfer scheduling problem. The aim is to provide service differentiation among different type of services (i.e., low and high priority data) and also to meet their QoS requirements. To achieve such a goal, we present the performance modeling and optimization framework based on a constrained Markov decision process (CMDP). The CMDP can be solved to obtain an optimal policy, which determines an action (i.e., to request for wireless energy transfer or to transmit a packet to an access point) of the node to take, given the current state. The objective is to maximize the weighted sum of throughput of low and high priority data. The constraint on the packet loss probabilities for both types of data is also imposed. We demonstrate the application of the proposed framework to optimize the performance of a data mule operated with energy transferred wirelessly from the access point. The numerical results show the success of meeting QoS requirement and achieving service differentiation.

II. SYSTEM MODEL

In this section, we first describe a general network model considered in this paper. Then, we present an overview of the performance modeling and optimization for a mobile node.

A. General Network Model

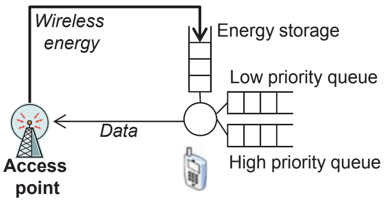


Fig. 1. System model.

We consider a mobile node which has an ability to transmit different types of data and to harvest wireless energy from an access point (Fig. 1). The mobile node collects two types of data (i.e., low and high priority data) and stores the packets into two separate queues. The queues have finite sizes denoted by Q_l and Q_h for low and high priority data, respectively. The low and high priority data could have different QoS requirements (e.g., packet loss probability and throughput). The mobile node can move in and out of the coverage area of the access point. If the mobile node is in the coverage area, it is able to transmit packets from the queues to the access point. Alternatively, the mobile node can inform the access point to transfer wireless energy. The access point, after receiving the request from the node, will release wireless energy with a predefined amount. In this case, the node will harvest and store wireless energy in its energy storage. The capacity of the energy storage is E units of energy. On the other hand, if the node is not in the coverage of the access point, it cannot transmit packets or request for wireless energy transfer from the access point. We assume that the node and access point operate on a time slot basis. Therefore, one time slot can be used either by the node to transmit a packet or by the access point to transfer wireless energy.

The mobile node operates (i.e., receives and stores incoming packets as well as transmits a packet from its queue) solely by using energy from its storage. If the energy storage is empty, the node will be automatically shut down and unable to receive or transmit a packet. However, we assume that the node is still able to contact the access point to transfer wireless energy, even the energy storage is empty. For example, the node may reserve a small amount of energy for such a request.

B. Performance Modeling and Optimization

The mobile node is facing a decision making problem when it is in the coverage of the access point. In particular, the node could request the access point to transfer wireless energy to replenish its energy storage. Alternatively, the node could transmit a packet from the queue of low or high priority data. The decision making problem must be solved to achieve the objective (i.e., maximizing weighted sum of throughput of low and high priority data) and meet the constraint (i.e., packet loss probability requirement). To obtain an optimal solution for this decision making problem, we formulate the constrained Markov decision process (CMDP) with the following modeling detail.

- *Mobility:* The mobile node can move among locations, whose set is denoted by $\mathcal{L} = \{0, 1, \ldots, L\}$. $\mathcal{L}_{\mathrm{A}} \subseteq \mathcal{L}$ is the set of locations that have the access point. L is the maximum number of locations. The probability that the mobile node will move from location l to location l' in one time slot is denoted by $M_{l,l'}$.
- *Packet arrival:* At location $l \in \mathcal{L}$, the probabilities of a packets arriving at the mobile node for the low and high priority data are denoted as $\alpha_{l,a}$ and $\lambda_{l,a}$, respectively, for $a = 0, 1, \ldots, A$ where A is the maximum arrival batch size.
- *Packet transmission:* If the mobile node is at location $l \in \mathcal{L}_{\mathrm{A}}$ (i.e., in the coverage of any access point) and decides to transmit a packet retrieved from the queue of either low or high priority data to the access point, the successful packet transmission probability is denoted by μ_l.
- *Wireless energy transfer:* If the mobile node is at location $l \in \mathcal{L}_{\mathrm{A}}$ and decides to request for the access point to transfer wireless energy, the probabilities that the node receives w units of energy (i.e., the energy level of the storage increases by w units) is denoted by $\sigma_{l,w}$ for $w = 0, 1, \ldots, W$ where W is the maximum amount of transferred energy.

III. OPTIMIZATION FORMULATION

In this section, we formulate a constrained Markov decision process (CMDP) to obtain the optimal policy for the mobile node. The optimal policy determines the action of the mobile node given the current state. Firstly, we define the state and action spaces of the CMDP. Then, we derive the transition probability matrix of the mobile node. Then, we formulate and solve the CMDP for the optimal policy.

A. State Space and Action Space

The state space of the mobile mode with data transmission and wireless energy transfer capabilities is defined as follows:

$$\begin{aligned} \Theta &= \Big\{(\mathscr{L}, \mathscr{E}, \mathscr{Q}_{\mathrm{l}}, \mathscr{Q}_{\mathrm{h}}); \mathscr{L} \in \mathcal{L}, \mathscr{E} \in \{0, 1, \ldots, E\}, \\ &\qquad \mathscr{Q}_{\mathrm{l}} \in \{0, 1, \ldots, Q_{\mathrm{l}}\}, \mathscr{Q}_{\mathrm{h}} \in \{0, 1, \ldots, Q_{\mathrm{h}}\}\Big\} \end{aligned} \quad (1)$$

where $\mathscr{L}$, $\mathscr{E}$, $\mathscr{Q}_{\mathrm{l}}$, and $\mathscr{Q}_{\mathrm{h}}$ are the random variables of location, energy level in the storage, the number of packets in the queues for low and high priority data, respectively. The state is then defined as a composite variable $\theta = (l, e, q_{\mathrm{l}}, q_{\mathrm{h}}) \in \Theta$, where l, e, q_{l}, and q_{h} are the corresponding variables of $\mathscr{L}$, $\mathscr{E}$, $\mathscr{Q}_{\mathrm{l}}$, and $\mathscr{Q}_{\mathrm{h}}$, respectively.

When the mobile node is at location $l \in \mathcal{L}_{\mathrm{A}}$, it is in the coverage of the access point. Therefore, in general, the action space of the node is defined as follows:

$$\Delta(\theta) = \begin{cases} \{0, 1, 2\}, & \text{if } l \in \mathcal{L}_{\mathrm{A}} \text{ and } e > 0 \\ \{0\}, & \text{if } l \in \mathcal{L}_{\mathrm{A}} \text{ and } e = 0 \\ \emptyset, & \text{otherwise} \end{cases} \quad (2)$$

where 0, 1, and 2 correspond to actions “request for wireless energy transfer”, “transmit a packet from the queue of low priority data”, and “transmit a packet from the queue of high priority data”, respectively. If the energy level in the energy storage of the node is zero, the node can only request the access point to transfer wireless energy, but not transmit any packet.

B. Transition Probability Matrix

In the following, we will derive the transition probability of the CMDP model according to the action of the node. We first consider the queue state transition for the high and low priority data. Then, we incorporate the energy state transition, and finally the location transition of the mobile node.

1) Queue State Transition: For the queue state transition of the high priority data, if there is no packet transmission (e.g., when the node is at location $l \in \mathcal{L} \setminus \mathcal{L}_{\mathrm{A}}$), but there is packet arrival, the transition matrix is given as follows:

$$\mathbf{H}_l = \begin{bmatrix} \lambda_{l,0} & \cdots & \lambda_{l,A} & & \\ & \ddots & \ddots & \ddots & \\ & & \lambda_{l,0} & \cdots & \lambda_{l,A} \\ & & & \ddots & \vdots \\ & & & & 1 \end{bmatrix} \tag{3}$$

where each row of this matrix corresponds to the number of packets in the queue of high priority data, i.e., $q_{\mathrm{h}} = 0, 1, \ldots, Q_{\mathrm{h}}$. On the other hand, if there is packet transmission (e.g., when the node is at location $l \in \mathcal{L}_{\mathrm{A}}$ and the action is to transmit a packet from the queue of high priority data), the transition matrix is given as in (4). Note that for the transition matrices in (3) and (4), if the packets arrive and the queue is full, some incoming packets will be dropped, which is considered to be the packet loss of high priority data.

If the energy storage of the node is empty or the node decides to request for wireless energy transfer from the access point, there is no change for the number of packets in the queue. Therefore, the transition matrix is denoted by an identity matrix $\mathbf{I}$, which in this case has the size of $Q_{\mathrm{h}}+1 \times Q_{\mathrm{h}}+1$.

Then, we consider the transition matrices of the queue state of the low priority data. The similar matrices to those of the high priority data can be derived. Firstly, if there is no packet transmission, but there is packet arrival for low priority data, the transition matrix is denoted by $\mathbf{L}_l$. The element of matrix $\mathbf{L}_l$ is similar to that of $\mathbf{H}_l$ in (3), except that $\lambda_{l,a}$ is replaced by $\alpha_{l,a}$. Secondly, if there is packet transmission for the low priority data, the transition matrix is denoted by $\hat{\mathbf{L}}_l$, whose element is similar to that of $\hat{\mathbf{H}}_l$ in (4), except that again $\lambda_{l,a}$ is replaced by $\alpha_{l,a}$. Similarly, if there is no change for the number of packets, the transition matrix for the queue state of low priority data is an identity matrix with the size of $Q_{\mathrm{l}} + 1 \times Q_{\mathrm{l}} + 1$.

2) Energy State Transition: The energy state transition depends on the action of the mobile node. Firstly, we consider the action that the mobile node requests for wireless energy transfer from the access point when the node is at location $l \in \mathcal{L}_{\mathrm{A}}$. The transition matrix is expressed as follows:

$$\mathbf{E}_l = \begin{bmatrix} \sigma_{l,0}\mathbf{I}\otimes\mathbf{I} & \cdots & \sigma_{l,W}\mathbf{I}\otimes\mathbf{I} & & \\ & \ddots & \ddots & \ddots & \\ & & \sigma_{l,0}\mathbf{L}_l\otimes\mathbf{H}_l & \cdots & \sigma_{l,W}\mathbf{L}_l\otimes\mathbf{H}_l \\ & & & \ddots & \vdots \\ & & & & \mathbf{L}_l\otimes\mathbf{H}_l \end{bmatrix} \tag{5}$$

where each row of the matrix $\mathbf{E}_l$ corresponds to the energy level in the storage of the node, i.e., $e = 0, 1, \ldots, E$. Since the first row of matrix $\mathbf{E}_l$ corresponds to the zero energy level (i.e., the energy storage is empty), there is no packet arrival for high and low priority data, and hence the identity matrices $\mathbf{I}$ are applied. Here $\otimes$ is the Kronecker product, which combines the queue state transition matrices of the low and high priority data together. These matrices are multiplied with the probability that the energy level in the storage can increase by w units (i.e., $\sigma_{l,w}$) when the node is at the location $l \in \mathcal{L}_{\mathrm{A}}$.

On the other hand, if there is no wireless energy transfer and there is packet arrival (e.g., the node is at location $l \in \mathcal{L} \setminus \mathcal{L}_{\mathrm{A}}$), the energy state transition matrix is defined as follows:

$$\hat{\mathbf{E}}_l = \begin{bmatrix} \mathbf{I}\otimes\mathbf{I} & & & & \\ \mathbf{L}_l\otimes\mathbf{H}_l & \mathbf{0} & & & \\ & \mathbf{L}_l\otimes\mathbf{H}_l & \mathbf{0} & & \\ & & \ddots & \ddots & \\ & & & \mathbf{L}_l\otimes\mathbf{H}_l & \mathbf{0} \end{bmatrix}. \tag{6}$$

In this case, the energy level will decrease by one unit due to consumption of the node.

Finally, if there is no wireless energy transfer, but there are packet arrival and transmission, the energy state transition matrix is denoted by $\tilde{\mathbf{E}}_l^{(1)}$ and $\tilde{\mathbf{E}}_l^{(2)}$ if the packet from the queue of low and high priority data is transmitted (i.e., actions "1" and "2"), respectively. The elements of these matrices $\tilde{\mathbf{E}}_l^{(1)}$ and $\tilde{\mathbf{E}}_l^{(2)}$ are similar to that of $\hat{\mathbf{E}}_l$ in (6), with the additional following detail.

- If the packet from the queue of low priority data is transmitted, the term $\mathbf{L}_l\otimes\mathbf{H}_l$ of $\hat{\mathbf{E}}_l$ in (6) will be replaced by $\hat{\mathbf{L}}_l \otimes \mathbf{H}_l$.
- If the packet from the queue of high priority data is transmitted, the term $\mathbf{L}_l\otimes\mathbf{H}_l$ of $\hat{\mathbf{E}}_l$ in (6) will be replaced by $\mathbf{L}_l \otimes \hat{\mathbf{H}}_l$.

3) Location State Transition: Finally, we derive the transition matrix for when the location state transition is incorporated with the energy level and queue state transitions.

For action "0" (i.e., the mobile node requests for wireless energy transfer), the transition matrix is denoted by $\mathbf{P}(0)$, whose element is obtained from

$$\begin{cases} M_{l,l'}\mathbf{E}_l, & l \in \mathcal{L}_{\mathrm{A}} \\ M_{l,l'}\hat{\mathbf{E}}_l & l \in \mathcal{L} \setminus \mathcal{L}_{\mathrm{A}}. \end{cases} \tag{7}$$

For action "1" (i.e., the node transmits the packet from the queue of the low priority data), the transition matrix is denoted by $\mathbf{P}(1)$, whose element is obtained from

$$\begin{cases} M_{l,l'}\tilde{\mathbf{E}}_l^{(1)}, & l \in \mathcal{L}_{\mathrm{A}} \\ M_{l,l'}\hat{\mathbf{E}}_l & l \in \mathcal{L} \setminus \mathcal{L}_{\mathrm{A}}. \end{cases} \tag{8}$$

For action "2" (i.e., the node transmits the packet from the queue of the high priority data), the transition matrix is denoted by $\mathbf{P}(2)$, whose element is obtained from

$$\begin{cases} M_{l,l'}\tilde{\mathbf{E}}_l^{(2)}, & l \in \mathcal{L}_{\mathrm{A}} \\ M_{l,l'}\hat{\mathbf{E}}_l & l \in \mathcal{L} \setminus \mathcal{L}_{\mathrm{A}}. \end{cases} \tag{9}$$

$$\hat{\mathbf{H}}_l = \left[\begin{array}{ccccc} \lambda_{l,0} & \cdots & \lambda_{l,A} & & \\ \mu_l\lambda_{l,0} & \cdots & \lambda_{l,a}\mu_l + \lambda_{l,a-1}(1-\mu_l) & \cdots & \lambda_{l,A}(1-\mu_l) \\ & \ddots & \ddots & \ddots & \ddots \\ & & & \mu_l\lambda_{l,0} & \sum_{a=1}^{A}\lambda_{l,a}\mu_l + \sum_{a'=0}^{A}\lambda_{l,a'}(1-\mu_l) \end{array} \right] \quad (4)$$

C. Optimal Policy

Given the state (i.e., location, energy level, the number of packets in queues), the node has to make a decision to request for wireless energy transfer or transmit a packet from the queue of low or high priority data. The mapping of the state to the action taken by the node is referred to as the policy denoted by π. The optimal policy is defined to achieve the maximum weighted sum of throughput of the low and high priority data, while the packet loss requirements are maintained below the thresholds. Formally, the optimization problem based on CMDP is expressed as follows:

$$\begin{aligned} \max_{\pi} \quad & \mathscr{J}_{\mathrm{T}}(\pi) = \lim_{t\to\infty}\inf \frac{1}{t}\sum_{t'=1}^{t}\mathbb{E}\left(\mathscr{T}(\theta_{t'},\delta_{t'})\right) \qquad (10) \\ \text{s.t.} \quad & \mathscr{J}_{\mathrm{L,l}}(\pi) = \lim_{t\to\infty}\sup \frac{1}{t}\sum_{t'=1}^{t}\mathbb{E}\left(\mathscr{L}_{\mathrm{l}}(\theta_{t'},\delta_{t'})\right) \leq L_{\mathrm{l}} \\ & \mathscr{J}_{\mathrm{L,h}}(\pi) = \lim_{t\to\infty}\sup \frac{1}{t}\sum_{t'=1}^{t}\mathbb{E}\left(\mathscr{L}_{\mathrm{h}}(\theta_{t'},\delta_{t'})\right) \leq L_{\mathrm{h}} \end{aligned}$$

where $\mathscr{J}_{\mathrm{T}}(\pi)$ is the function of weighted sum of throughput, $\mathscr{J}_{\mathrm{L,l}}(\pi)$ and $\mathscr{J}_{\mathrm{L,h}}(\pi)$ are the functions of packet loss probability of the low and high priority data, respectively. $\mathscr{T}(\theta_{t'},\delta_{t'})$, $\mathscr{L}_{\mathrm{l}}(\theta_{t'},\delta_{t'})$, and $\mathscr{L}_{\mathrm{h}}(\theta_{t'},\delta_{t'})$ are their immediate functions given state $\theta_{t'} \in \Theta$ and action $\delta_{t'} \in \Delta$ at time t'. L_{l} and L_{h} are the packet loss requirements for the low and high priority data, respectively.

The function immediate of weighted sum of throughput is defined as

$$\mathscr{T}(\theta,\delta) = \omega_{\mathrm{l}}\tilde{\mu}_{\mathrm{l}} + \omega_{\mathrm{h}}\tilde{\mu}_{\mathrm{h}} \qquad (11)$$

where ω_{l} and ω_{h} are the weights of the successful packet transmission probabilities (i.e., $\tilde{\mu}_{\mathrm{l}}$ and $\tilde{\mu}_{\mathrm{h}}$) for low and high priority data, respectively. $\tilde{\mu}_{\mathrm{l}} = \mu_l$ if $l \in \mathcal{L}_{\mathrm{A}}$, $e > 0$, $q_{\mathrm{h}} > 0$ and $\delta = 1$; otherwise $\tilde{\mu}_{\mathrm{l}} = 0$. Similarly, $\tilde{\mu}_{\mathrm{h}} = \mu_l$ if $l \in \mathcal{L}_{\mathrm{A}}$, $e > 0$, $q_{\mathrm{h}} > 0$ and $\delta = 2$; otherwise $\tilde{\mu}_{\mathrm{h}} = 0$.

The function of immediate packet loss probability for the low priority data is defined as follows:

$$\mathscr{L}_{\mathrm{l}}(\theta,\delta) = \begin{cases} 1, & e = 0 \\ \frac{\sum_{a=Q_{\mathrm{l}}-q_{\mathrm{l}}+1}^{A}\alpha_{l,a}}{\overline{\alpha}_l}, & q_{\mathrm{l}} + A > Q_{\mathrm{l}} \text{ and } e > 0 \\ 0, & \text{otherwise} \end{cases} \qquad (12)$$

where $\overline{\alpha}_l$ is the average packet arrival rate of the low priority data at location l, obtained from $\overline{\alpha}_l = \sum_{a=1}^{A} a\alpha_{l,a}$. Similarly, the function of immediate packet loss probability for the high priority data is defined as follows:

$$\mathscr{L}_{\mathrm{h}}(\theta,\delta) = \begin{cases} 1, & e = 0 \\ \frac{\sum_{a=Q_{\mathrm{h}}-q_{\mathrm{h}}+1}^{A}\lambda_{l,a}}{\overline{\lambda}_l}, & q_{\mathrm{h}} + A > Q_{\mathrm{h}} \text{ and } e > 0 \\ 0, & \text{otherwise} \end{cases} \qquad (13)$$

where $\overline{\lambda}_l$ is the average packet arrival rate of the high priority data at location l, obtained from $\overline{\lambda}_l = \sum_{a=1}^{A} a\lambda_{l,a}$.

Then, we obtain the optimal policy of the CMDP by formulating and solving an equivalent linear programming (LP) problem. The LP problem is expressed as follows:

$$\begin{aligned} \max_{\phi(\theta,\delta)} \quad & \sum_{\theta\in\Theta}\sum_{\delta\in\Delta}\phi(\theta,\delta)\mathscr{T}(\theta,\delta) \qquad (14) \\ \text{s.t.} \quad & \sum_{\theta\in\Theta}\sum_{\delta\in\Delta}\phi(\theta,\delta)\mathscr{L}_{\mathrm{l}}(\theta,\delta) \leq L_{\mathrm{l}} \\ & \sum_{\theta\in\Theta}\sum_{\delta\in\Delta}\phi(\theta,\delta)\mathscr{L}_{\mathrm{h}}(\theta,\delta) \leq L_{\mathrm{h}} \\ & \sum_{\delta\in\Delta}\phi(\theta',\delta) = \sum_{\theta\in\Theta}\sum_{\delta\in\Delta}\phi(\theta,\delta)P_{\theta,\theta'}(\delta), \quad \theta' \in \Theta \\ & \sum_{\theta\in\Theta}\sum_{\delta\in\Delta}\phi(\theta,\delta) = 1, \quad \phi(\theta,\delta) \geq 0 \end{aligned}$$

where $P_{\theta,\theta'}(\delta)$ denotes the element of matrix $\mathbf{P}(\delta)$ where $\theta = (s,b,q)$ and $\theta' = (s',b',q')$. Let the solution of the LP problem be denoted by $\phi^*(\theta,\delta)$. The randomized policy of the node can be obtained as follows:

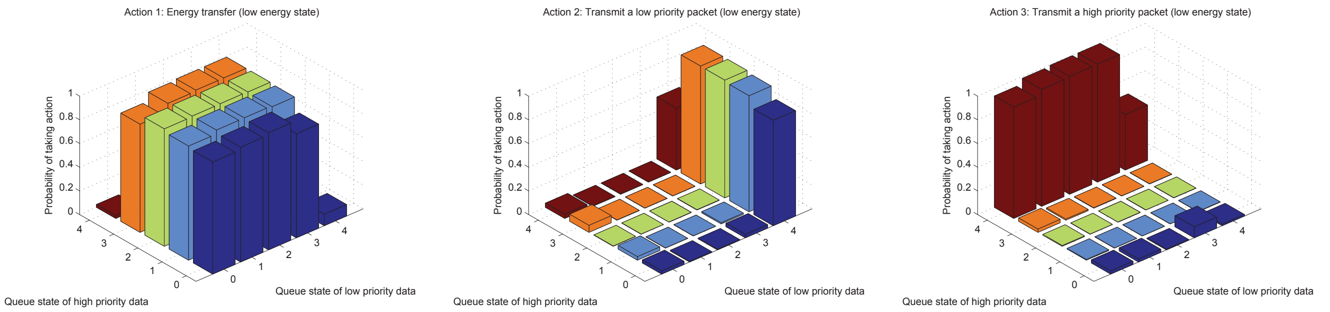
$$\pi^*(\theta,\delta) = \frac{\phi^*(\theta,\delta)}{\sum_{\delta'\in\Delta}\phi^*(\theta,\delta')}, \text{ for } \theta \in \Theta \text{ and } \sum_{\delta'\in\Delta}\phi^*(\theta,\delta') > 0. \qquad (15)$$

If $\sum_{\delta'\in\Delta}\phi^*(\theta,\delta') = 0$, then $\pi^*(\theta,0) = 1$ and $\pi^*(\theta,1) = \pi^*(\theta,2) = 0$ (i.e., the node will request for wireless energy transfer).

IV. PERFORMANCE EVALUATION

A. Parameter Setting

We consider a mobile data mule (i.e., a mobile node) traveling to collect data from the sensors. In this case, the sensors are not in the coverage of the access point. The data mule moves, collects and stores data from sensors in its queues, depending on the type whether it is high or low priority data. The data mule when moving into the coverage of the access point, can choose to request for wireless energy transfer, or to transmit its packets (i.e., from the queue of low or high priority data). On the other hand, when the data mule moves to collect data from sensors, it cannot connect with the access point. Figure 2 shows an example of the scenario in

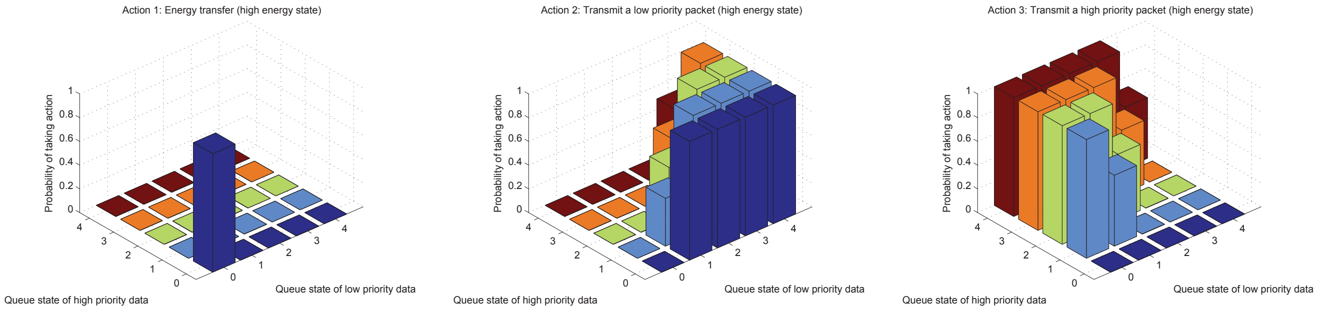

Action 1: Energy transfer (low energy state)

Action 2: Transmit a low priority packet (low energy state)

Action 3: Transmit a high priority packet (low energy state)

(a) (b) (c)

Fig. 3. Optimal policy of a node for actions (a) to request for wireless energy transfer, (b) to transmit a packet of low priority traffic, and (c) to transmit a packet of high priority traffic, when the energy state is low ($e = 5$).


Action 1: Energy transfer (high energy state)

Action 2: Transmit a low priority packet (high energy state)

Action 3: Transmit a high priority packet (high energy state)

(a) (b) (c)

Fig. 4. Optimal policy of a node for actions (a) to request for wireless energy transfer, (b) to transmit a packet of low priority traffic, and (c) to transmit a packet of high priority traffic, when the energy state is high ($e = 55$).

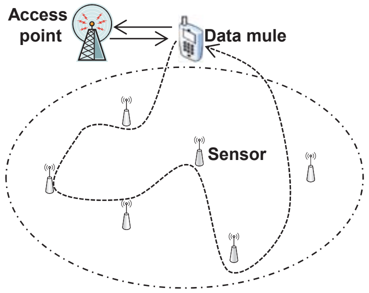


Fig. 2. Example scenario of data mule.

the performance evaluation. Note that this scenario is similar to the delay tolerant network (DTN).

The data mule has an energy storage with the size of 60 units of energy. The maximum queue sizes for low and high priority data are 4 packets. The data mule spends 50% of the time at the access point. When the data mule is not in the coverage area of the access point, it receives a packet from any sensor with probabilities of 0.05 for both low and high priority data. These are the packet arrival rates of the data mule. The successful packet transmission probability of the data mule to the access point is 0.99. The successful wireless energy transfer is 0.98. If the energy transfer is successful, the data mule will receive 4 units of energy. The throughput weights of low and high priority data are 1 and 2, respectively. There is no packet loss probability requirement for the low priority data, but it is at 0.07 for the high priority data. For comparison purpose, we consider a static policy in which the data mule, if is in the coverage of the access point, chooses three actions with equal probabilities.

B. Numerical Results

Figures 3 and 4 show the optimal policy of the data mule obtained from solving the optimization problem. Figure 3 is for when the energy level in the storage of the data mule is 5 units, while that of Fig. 4 is 55 units. Clearly, when the energy level is low (i.e., 5 units), the optimal policy will let the data mule mostly request for wireless energy transfer (Fig. 3(a)), except when the queue is full. If the queue is full, the data mule should transmit the packet to the access point (i.e., Fig. 3(b) and Fig. 3(c) for low and high priority data, respectively). On the other hand, when the energy level is high, the data mule, when is in the coverage of the access point, will transmit the packet (Fig. 4(b) and Fig. 4(c) for low and high priority data, respectively). In this case, the weight of the low and high priority data will control the probability of packet transmission to meet the performance requirements. Note that if both the queues are empty, the data mule will decide to request for wireless energy transfer (Fig. 4(a)).

Next, we evaluate the effectiveness of the optimal policy, Fig. 5 shows the throughput of low and high priority data

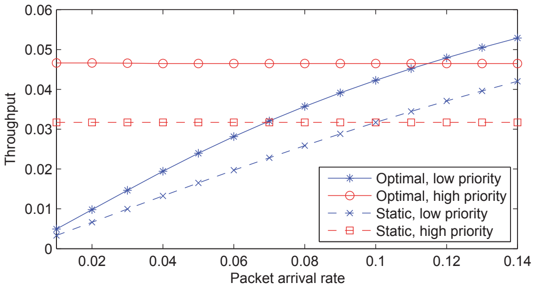


Fig. 5. Throughput under different packet arrival rate of low priority data.

when the packet arrival rate of the low priority data is varied. As expected, when the packet arrival rate of the low priority data increases, its throughput increases. However, due to the separation of the queues, the throughput of the high priority data is not affected and the packet loss probability is maintained at the target level (i.e., 0.07, which corresponds to the throughput of 0.0465 packets per time slot as shown in Fig. 5). Also, Fig. 5 shows the throughput of the static policy. Clearly, the static policy achieves much lower throughput.

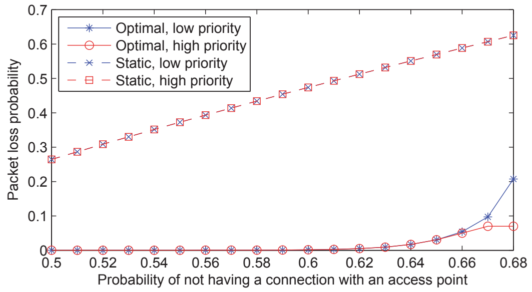


Fig. 6. Packet loss probability under different mobility parameter.

Figure 6 shows the packet loss probability when the probability that the data mule is out of the coverage area (and hence does not have a connection with the access point) is varied. As expected, when the data mule has lower chance to be in the coverage of the access point, the performance drops (i.e., higher packet loss probability). However, with the optimal policy, the packet loss requirement of the high priority data is still maintained at the threshold, while that of the low priority data is unbounded. This result clearly shows that the optimization can provide the optimal policy to successfully achieve the QoS differentiation. Again, the packet loss probabilities from the static policy are the same indicating the failure of providing service differentiation and are much higher than those of the optimal policy.

V. SUMMARY

We have presented the performance modeling and optimization framework for a mobile node in the network with wireless energy transfer. The mobile node can request for wireless energy transfer or transmit a packet to an access point. The service differentiation between low and high priority data has been implemented in the mobile node where the separate queues are used to store incoming packets. The scheduling decision of the mobile node can be optimized based on a constrained Markov decision process. Its optimal policy is to maximize the weighted sum of throughput while maintaining packet loss probability below the threshold. The numerical results show that the optimal policy can successfully achieve the objective and meet the constraint for low and high priority data.

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