Optimal Control of Harvest-Or-Access Protocol for Slotted ALOHA Network with Energy Harvesting

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에너지 하베스팅을 갖춘 Slotted ALOHA 네트워크를 위한 Harvest-Or-Access 프로토콜의 최적 제어 알고리즘

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Abstract

In this paper, we introduce the 'Harvest-Or-Access' protocol which utilizes idle slots in slotted ALOHA operations as opportunities for wireless energy transfer, thereby enhancing the efficiency of wireless spectrum resource utilization [1]. To maximize system throughput for slotted ALOHA network with energy harvesting, we model the system as a Markov decision process (MDP) from the hybrid access point (HAP) perspective. The decision process for this problem considers an infinite time sequence ($T \to \infty$), or infinite horizon problem. To solve this infinite horizon problem, we use value iteration algorithms based on MDP. These provide an optimal control method for slotted ALOHA. Numerical simulation results demonstrate the effectiveness of our proposed method.

Ⅰ. Introduction

With the development of wireless communication technology, radio frequency (RF) signals have become ubiquitous. Wireless Powered Communication Network (WPCN) system has received great attention as an emerging network system capable of converting radio frequency signals into direct current. WPCN includes wireless energy transfer (WET) in the downlink and wireless information transfer (WIT) in the uplink. As a promising technology for future networks, extensive studies have been introduced on the energy harvesting networks [2]. To achieve maximum throughput of the WPCN, we transform the problem of maximizing throughput into the problem of maximizing the average expected reward under the model of Markov decision process (MDP). It is equivalent to the problem of finding the optimal policy using the value iteration algorithm in the infinite horizon problem. At the beginning of each slot, the hybrid access point (HAP) broadcasts the transmission probability obtained by the optimal policy, which can effectively improve the throughput of the system.

Ⅱ. Method

we assume that a HAP provides wireless network services and energy to N nodes in a specific area. On the HAP side, if no signal is detected at the beginning of each slot, the HAP decides that the current slot is idle and uses the remaining time of the idle slot for power transfer. In this system, the HAP and the nodes operate in half-duplex mode. Each fully charged node performs the WIT process with probability p in each slot, where the HAP broadcasts p at the beginning of each slot for node's use. Each node has the same battery capacity, equal to the energy consumed to transmit a packet. Once a node transmits a packet, it shall wait Z idle slots on the average to get back into contention. Considering a simple charging model, each node can be fully charged with probability $q = 1/Z$. For further discussion, we define the following probabilities:

$$p_i = \binom{K}{i} p^i (1-p)^{K-i}, i = 0, \dots, K, \quad (1)$$

$$q_j = \binom{N-K}{j} q^j (1-q)^{N-K-j}, j = 0, \dots, N-K, \quad (2)$$

where K denots the number of active nodes who already harvested energy and have packets to transmit.

In traditional slotted ALOHA systems, where nodes do not rely on energy harvesting, the optimal probability of packet transmission to maximize throughput is given by $p = 1/K$ where K represents the number of nodes in the system that have packet to transmit. On the other hand, the nodes of the slotted ALOHA network with energy harvesting frequently have no energy to transmit. Therefore, it is necessary to re-find the optimal transmission probability to maximize throughput. To focus on the effect of energy harvesting at each node, we assume that the nodes always have packets to transmit. Here we define the nodes in the system which have harvested enough energy and have packet to transmit as active node. Consequently, we have the number of active nodes equal to the number of fully charged nodes, denoted as K. We describe the system state transition as an Markov chain as shown in Fig. 1 where each state is defined as the number of active nodes.

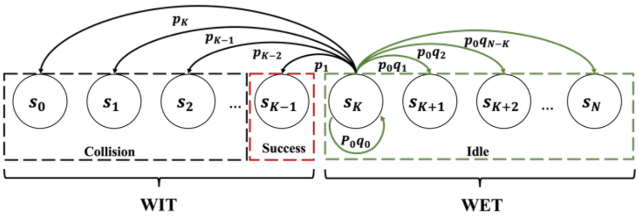

Fig. 1. Discrete Markov-chain model for our system.

We apply an MDP at the HAP side to find the optimal state dependent actions, where at each discrete decision epoch, the decision maker chooses the action broadcast based on the state. Here the state is the number of currently active nodes denoted as $s \in \mathbb{S} = \{0, 1, 2, \dots, N\}$, the action is the transmission probability denoted as $a \in \mathbb{A} = \{0, 0.01, 0.02, \dots, 1\}$, the transition probabilities denoted as $p(s'|s, a)$, and the reward denoted as $r(s, a) \in \{0, 1\}$.

The Bellman optimality equation (BOE) describes the optimal state values of the optimal policies as follows
$v(s) = \max_{\pi} \sum_a \pi(a \mid s)\left(\sum_r p(r \mid s, a) r + \gamma \sum_{s'} p(s' \mid s, a) v(s')\right)$,
where γ is the discount factor. If state value $v_{\pi_1}(s) \geq v_{\pi_2}(s), \forall s \in \mathbb{S}$ we say that policy π_1 is better than policy π_2. As the iteration g increases, if the convergence condition is satisfied and a π^* is better than all other policies, then π^* is the optimal policy.

Algorithm 1 is a pseudocode display of this process.

Algorithm 1 Value Iteration Algorithm (Infinite Horizon)

Input: MDP: $\mathbb{S}$, $\mathbb{A}$, $p(s' \mid s, a)$, $p(r \mid s, a)$, γ, $T \to \infty$, ε;
Output: $\pi^*(s)$, $s \in \mathbb{S}$;
Initialize $v_0(s) = 0$
while converge == False **do**
  for $K = 0$; $K = N$; $K{+}{+}$ **do**
    $v_{g+1}(s) = \max_a \left(\sum_r p(r \mid s, a) r + \gamma \sum_{s'} p(s' \mid s, a) v_g(s')\right)$
  end for
  if $\|v_g - v_{g-1}\| < \varepsilon(1-\gamma)/\gamma$ **then**
    converge = True
  end if
end while
for $K = 0$; $K = N$; $K{+}{+}$ **do**
  $\pi^*(s) = \arg\max_a \left(\sum_r p(r \mid s, a) r + \gamma \sum_{s'} p(s' \mid s, a) v_g(s')\right)$
end for

here $\varepsilon = 10^{-5}$ is the convergence related parameter.

With the value iteration algorithm for the infinite horizon problem, we obtain the optimal transmission policy. Then, we bring this set of optimal transmission probabilities to the proposed system.

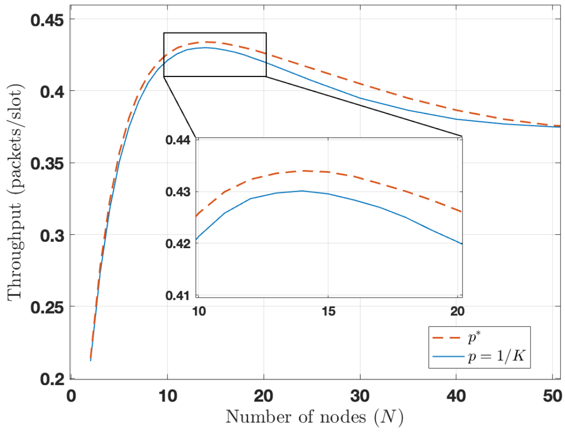

Fig. 2. Throughput over number of nodes (N).

Fig. 2 shows the variation of throughput over the number of nodes N for the policy $p = 1/K$ which is optimal for the conventional ALOHA networks, and our proposed optimal policy p^*. As the number of nodes N increases, the optimal policy obtained by MDP always has a higher throughput than the conventional policy, which indicates that the transmission probability we obtained can effectively improve the throughput of the system.

Ⅲ. Conclusion

In this paper, we consider an optimal access control algorithm in a slotted ALOHA network with energy harvesting where the HAP makes the nodes transmit packets using the transmission probability under the optimal policy based on the number of active nodes. Numerical results show that the proposed algorithm improves the throughput of the system. In future work, we consider incorporating the active node estimation and introducing delay as a performance metric for analysis.

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