

The Scheme of Power Allocation for Decode-and-Forward Relay Channel in Energy Harvesting WSNs

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Abstract

Recently, the issue of excessive energy consumption in wireless communications has become increasing critical, and the energy harvesting as a renewable energy resource, has received extensive attractions. In this paper, a wireless sensor network (WSN) is considered, where the source-destination pair communicates via an energy harvesting relay links. We study the problem of the harvested energy distribution among the source, relay and destination nodes. An effective power allocation scheme is developed which exploits the decode-and-forward (DF) relaying strategy and channel state information. The outage probability is analyzed and simulation results show that the outage performance for two sub-channels is always performs well in the cases of different threshold target data rate. Moreover, the effect of the different radio of the optimal sub-channel gain and Rayleigh channel gain on the outage performance is evaluated.

***Keywords:** Wireless sensor works, energy harvesting, power allocation, outage probability*

1. Introduction

In wireless sensor networks (WSNs), sensors nodes typically sense interesting information from surrounding environments and report data to a sink node via multi-hop wireless communication links [1]. Due to the low cost and self-configuring characteristics of wireless sensors, WSNs have exhibited great potentials in various applications, such as security surveillance, environment monitoring, wildlife preservation, and disaster relief [2]. The nodes are usually equipped with battery, which is fixed energy supply device and has limited operating time. When thousands of nodes are scattered in a toxic and hostile monitoring fields, it is impossible to recharge or replace battery. As nodes are severely energy constrained, the equipped battery must be used carefully.

The rapid growth in wireless applications, has brought inevitably the increasing rigidity of industrial standard as well as the dramatic rising of energy cost, issues in energy consumption is becoming more and more critical [3]. The energy conserving remains a critical challenge for increasing the node lifespan, which addresses the solutions for improving the energy efficiency. Energy harvesting is considered as an alternative to supplement batteries and has become increasing attractive in alleviating energy deficiency [4]. Unlike the conventional energy constrained systems, the energy harvesting systems powered by renewable sources [5], which aims to achieve the perpetual wireless communication links without the heavy operation overheads of replacing the batteries.

One approach of energy harvesting is to scavenge energy form the surrounding energy sources [6]. Some examples of energy sources include solar, wind, temperature variations and biochemical processes *etc.* The drawback of the energy scavenging approach, however, is the high reliance on unpredictable surrounding environments. For example, the solar-powered nodes may fail to work if sufficient

sunshine is not available. Another approach of energy harvesting is to distribute energy from the energy rich nodes to the energy hungry nodes. For the ultra-power applications, such as the ubiquitous sensing and forwarding data in WSNs, energy distributing through radio frequency (RF) signals is highly desirable [7]. The idea of simultaneous power and information delivery was proposed firstly in [8] for flat fading channel, which addressed the tradeoff between energy and information rate in point-to-point communication systems, and further extended to frequency selective channel.

In this paper, an energy harvesting WSN is considered, in which multiple pairs of source nodes and destination nodes communicate through relay links. In detail, the relay nodes receive the information sent from the source nodes via orthogonal channels, such as different time slots. And, the powered relay nodes forward the data to the destination nodes. The battery of relay nodes is assumed to be large enough to accumulate a significantly amount of power for relay links. The effective power allocation among multiple nodes is discussed and the performance of the outage probability is evaluated with the available radio channel information.

The remainder of the paper is organized as follows. Section 2 is dedicated to an overview of related works. Section 3 introduces the model and assumptions. Section 4 presents a channel gain maximum power allocation scheme. Section 5 provides the evaluation results for the proposed scheme and Section 6 concludes the paper.

2. Related Work

The difficulty for energy harvesting WSNs is that the practical circuits cannot execute energy harvesting and information detection from RF signals simultaneously. There exist three main relaying protocols: amplify and forward (AF), decode and forward (DF) and compress and forward (CF). In [9], a general receiver framework is introduced, which appeals a manner of time sharing or power splitting for energy harvesting and data detection. The impact of power splitting on the tradeoff between energy and achievable information rate is addressed in [10], and its difference from time sharing is highlighted in broadcasting scenarios in [11]. The outage probability for AF relay systems is studied in [12] for the one source-destination pair.

DF relaying protocol provides a proper option for adaptation as if the relay fails to decode any users' data, the relay can be paired with the other one. Regularly, communications become beneficial when the relay is placed nearby the source since the channel quality between the source and relay defines whether the relay can successfully decode the source's information or not. Also, from the energy harvesting point of view, if the relay is close to the source, the relay can obtain the sufficient energy from the source's transmission in a short time. From these observations, DF is more appropriate for energy harvesting cooperation. In [13], a new cooperative diversity technique based on DF is proposed. By exploiting the relay's proximity advantage over the destination, diversity gain can be gained with consuming neither extra energy nor extra bandwidth. The outage probability is analyzed and shows that the DF cooperation can achieve the diversity order of two (full diversity) in three node cooperation scenario. [14] consider the transmit power allocation schemes for a single link DF relay system, where the source and the relay transmit signals using the energy harvested from the surrounding environment. An offline and several online joint source and relay transmit power allocation schemes have been proposed, and the optimal power allocation is discussed.

In [15], it mainly investigated the performance of cooperative networks aided by energy harvesting relay node in terms of outage behavior in slow fading scenario.

From a perspective of systematic level, an on-off Markov model was proposed to characterize the stochastic property of harvested energy flow. In [16], a sum-throughput maximization problem in a two-way relay channel where all nodes are energy harvesting with limited battery storage is investigated. The DF, CF and AF relaying strategies with full-duplex and half-duplex radios are all considered. Furthermore, the relay selection problem is investigated in [17] for energy harvesting communication system. The relay nodes are dual nodes with energy harvesting and wireless information transfer capabilities. Based on the channel state information availability, two simple relay selection schemes are discussed. The outage performance of both schemes is studied numerically. The results show that the availability of channel state information at relays improves performance considerably. Moreover, energy harvesting efficiency of the relay nodes is a limiting factor for the outage performance of the schemes and there is a tradeoff associated involving number of relays in the system versus energy harvesting efficiency of the relays.

These papers mainly focus on the optimization of sum-throughput or outage probability maximization problem with the DF relay. But the character of relay links is not claimed. In this paper, we further study this problem to reduce outage probability for DF relay strategy in energy harvesting WSNs. Since the sensor nodes transmit and forward information by RF signals, the radio channel, including relay links must be major concerned for optimizing a WSN network. An effective power allocation among multiple nodes is proposed and the outage probability is evaluated by simulations.

3. System Model

We consider the general three-node relay channel in energy harvesting WSN, which consists of one source-destination pair and one relay, shown in Figure 1 [18]. It is assumed that the relay node operates in a half-duplex mode, that is, the relay transmission and receiving over two orthogonal channels, such as different time slots. All the channels are assumed to be in independently and identically quasi-static Rayleigh fading.

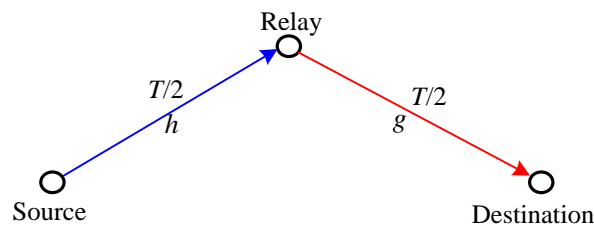


Figure 1. Three-node Energy Harvesting Relay Channel

For the energy harvesting relay, the battery of energy constrained relay can be recharged by the energy from its observations [19]. With the plenty of harvested power, instead of the limited battery power, the reliable relay transmission is ensured. As a result, the energy stored in the relay battery is only used for information detection from RF signals, which is important to prolong the lifespan of the relay link.

The power splitting manner in [9, 12] and decode-and-forward (DF) strategy are used for our energy harvesting relay model. As shown in Figure 1, the transmission consists of two phases, *i.e.*, two time slots of duration $T/2$. During the first time slot, the relay splits the RF signals from the source node into two streams, one for energy harvesting for relay

channel and the other for information detection. For the second time slot, the relay node forward the information from the source to the destination node if the information is reliable detected.

4. Channel Gain Maximum Power Allocation Scheme

In energy harvesting WSN, since the sensor nodes exchange information only by RF signals, the radio channel is the major concern when optimizing a WSN system. Some studies [20-22] have revealed that the radio link quality between the low power sensor nodes varies significantly with time and surrounding environments. Therefore, a fixed radio configuration, such as, constant transmission power on fixed radio channel, might not be effective, especially in military surveillance *etc.* If the sensor nodes are aware of the channel state information, the transmission power can be dynamically adapted to the link variations.

In the proposed scheme, the Rayleigh fading channel in both two time slots is divided into multiple flat fading sub-channels, and the RF signals are transmitted only by the sub-channel with the optimal channel gain for reliable information detection. Assume that the duration of RF signal from the i th source node is denoted by T_s , and the required bandwidth for Rayleigh fading channel between i th source-relay node pair, is given by

$$B = (1 + \alpha) \frac{1}{T_s}. \quad (1)$$

where $0 < \alpha \leq 1$. Let the delay spread of RF signal be τ_1 , then the number of resolvable paths of the channel, is expressed by

$$L_1 = \left\lfloor \frac{\tau_1}{T_s} \right\rfloor + 1. \quad (2)$$

The coherence bandwidth, Δf_1 can be written as

$$\Delta f_1 \approx \frac{1}{\tau_1}. \quad (3)$$

We divide B into M_1 equi-width sub-channels for the i th source-relay node pair, as well as M_2 equi-width sub-channels for the i th relay-destination node pair, and the bandwidth of sub-channel as M_1 for example, is

$$B_{sub1} = \frac{B}{M_1} = (1 + \alpha) \frac{1}{M_1 T_s}. \quad (4)$$

Then, the number of sub-channels, M_1 , is determined to meet the following constraints: 1) each sub-channel is flat fading, *i.e.*, $\tau_1 \leq M_1 T_s$; 2) all the sub-channels are subject to independent fading, *i.e.*, $B_{sub1} \geq \Delta f_1$. These two conditions are satisfied if

$$\frac{\tau_1}{T_s} \leq M_1 \leq (1 + \alpha) \frac{\tau_1}{T_s}. \quad (5)$$

To ensure the left inequality of (5), we choose $M_1 = L_1$, and to ensure the right inequality, we choose $\alpha \geq T_s / \tau_1$. Similarly, the parameter M_2 can be determined by eq. (2)-(5).

Let θ be the power splitting coefficient of the i th node pair, *i.e.*, the fraction of the source node used for energy harvesting. At the end of the first time slot, the information detection at the relay node is based on the following expression [19]

$$y_r = \sqrt{(1 - q) P h \beta_1} s + n_r. \quad (6)$$

where P is the transmission power of i th source node, h is the Rayleigh channel gain between the i th source node and the relay node, β_1 is the radio of the optimal sub-channel gain and Rayleigh channel gain between the i th source node and the relay node, s is the source information with unit power, and n_r is the additive white Gaussian noise (AWGN) with unit variance. In fact, such noise consists of the sampled AWGN coming from the RF to baseband signal conversion, and the baseband AWGN. We consider a pessimistic

case where only the signal power is reduced by power splitting, but not to the noise power, which provide the energy harvesting WSN with a lower and practical bound for relay transmission.

We consider the DF strategy used for the energy harvesting relay model, which requires the relay node to decode the source information successfully. The data rate at which the relay node decodes the i th source node, is

$$R_r = \frac{1}{2M_1} \log \left(1 + M_1 (1 - \theta) P |h|^2 \beta_1^2 \right). \quad (7)$$

For the pre-defined targeted rate R , the parameter θ is set to satisfy the criterion $R_r = R$, *i.e.*,

$$\theta \triangleq 1 - \frac{2^{2RM_1} - 1}{P |h|^2 \beta_1^2 M_1}. \quad (8)$$

The power splitting coefficient θ calculated by (8) is optimal for DF strategy. Each relay node can ideally transmit R (a pre-defined threshold) bits per second to ensure that relays are not over-loaded and the efficiency of the energy harvesting system is maintained at the expected level. If the relay node tries to transmit more bits than it is capable of, the relay efficiency decreases in the sense, because the source nodes have to wait longer for their turn to get the share of the relay transmission. A high network throughput or a low outage probability can be achieved by optimizing the parameter θ in energy harvesting WSN. The power splitting coefficient θ helps in efficient MAC functions and load balancing because it is always desirable for a relay node to transmit up to a certain number of bits per second for relay link.

At the end of the first time slot, the relay node harvested energy from the i th source node, is expressed by

$$E_H = \eta P |h|^2 \beta_1^2 \theta \frac{T}{2}. \quad (9)$$

where η is the energy harvesting efficient factor. For the second time slot, the harvested energy E_H is used to power the relay transmission. Since different power allocation schemes have different impacts on the system performances, the transmission power must be dynamically adapted to the relay link variations to maintain good performances.

During the second time slot, the energy harvested from the i th source node, is allocated to the optimal sub-channel for the i th relay-destination node pair. The transmission power in such sub-channel for the i th destination node is

$$P_r \triangleq \frac{E_H}{T/2} = \eta P |h|^2 \beta_1^2 \theta. \quad (10)$$

The relay node forwards the information from the i th source node if the information is reliably detected, *i.e.*, the following condition is satisfied

$$|h|^2 \beta_1^2 > \frac{2^{2RM_1} - 1}{PM_1}. \quad (11)$$

Then, provided there is a successful information detection at the relay node, the i th destination node receive the expression as

$$y_d = \sqrt{P_r} g \beta_2 s + n_d. \quad (12)$$

where g is the Rayleigh channel gain between the relay node and the i th destination node, β_2 is the radio of the optimal sub-channel gain and Rayleigh channel gain between the relay node and the i th destination node, and n_d is the noise at the destination. Without loss of generality, it is assumed that n_d has the same unit variance as that at the relay node. The data rate at the i th destination node is

$$R_d = \frac{1}{2M_2} \log\left(1 + M_2 P_r |g|^2 \beta_2^2\right) = \frac{1}{2M_2} \log\left(1 + M_2 \eta \theta P |h|^2 \beta_1^2 |g|^2 \beta_2^2\right) \cdot |h|^2 \beta_1^2 > \frac{2^{2RM_1-1}}{PM_1}. \quad (13)$$

The outage probability for the i th node pair is written as

$$\begin{aligned} P_{out} &= \Pr\left(\frac{1}{2M_1} \log\left(1 + M_1 P |h|^2 \beta_1^2\right) < R\right) + \Pr\left(\frac{1}{2M_1} \log\left(1 + M_1 P |h|^2 \beta_1^2\right) > R, R_d < R\right) \\ &= \Pr\left(\frac{1}{2M_1} \log\left(1 + M_1 P |h|^2 \beta_1^2\right) < R\right) + \Pr\left(\begin{array}{l} \frac{1}{2M_1} \log\left(1 + M_1 P |h|^2 \beta_1^2\right) > R, \\ \frac{1}{2M_2} \log\left(1 + M_2 \eta \theta P |h|^2 \beta_1^2 |g|^2 \beta_2^2\right) < R \end{array}\right) \end{aligned} \quad (14)$$

5. Simulation

In this section, we evaluate the performance of the proposed power allocation scheme for decode-and-forward relay channel in energy harvesting WSNs. In the simulation, one source-destination pair is considered, and all the channel coefficients are assumed to be complex Gaussian distribution with zero means and unit variances. The energy harvesting efficient factor is $\eta=1$. For comparison, we have implemented the single carrier power allocation scheme, whose outage probability performance can be used as a benchmark.

We first examine the outage probability under different number of sub-channels for source-relay node pair, as well as relay-destination node pair. The simulation results are shown in Figure 2, Figure 3 and Figure 4, where the ratio of the optimal sub-channel gain and Rayleigh channel gain between the source node and the relay node, is fixed to be $\beta_1=2$, and the ratio of the optimal sub-channel gain and Rayleigh channel gain between the relay node and the destination node is $\beta_2=2$, by varying the SNR from 10dB to 40dB in a step of 5dB. For the minimum SNR (10dB), the maximum data rate $R_{max}=1.73$ bit/s by Shannon's theory. Therefore, the target data rate must be carefully set to be less than or equal to the maximum data rate. In Figure 2, Figure 3 and Figure 4, the threshold target data rate is set to be $0.2R_{max}$, $0.6R_{max}$ and R_{max} , respectively.

In Figure 2, Figure 3 and Figure 4, the outage probability performance is improved along with the expected SNR. The reason is that, the data rate at which the relay node decodes the source node, and the data rate at the destination increase when the SNR grows. Also, we observed that outage probability performance deteriorates with the increasing threshold target data rate. With higher threshold data rate, it is more likely that the data rate at which the relay node decodes the source node is less than the threshold data rate, as well as the data rate at the destination. In addition, it is surprising to find that the outage probability of the proposed power allocation scheme for $M_1=2$ and $M_2=2$, always has the superior performance for different threshold target data rate. It might be due to the fact that the optimal sub-channel transmission scheme can benefit from high SNR, exclusively for $M_1=2$ and $M_2=2$.

In Figure 5, we study the outage probability at fixed $M_1=2$ and $M_2=2$, by varying β_1 and β_2 . It can be seen that the outage probability of the proposed power allocation scheme decreases when the β_1 and β_2 grows. This is because that when β_1 and β_2 increases, the proposed power allocation scheme can improve the transmission both from the source to the relay and the relay to the destination, but not the single carrier case. In particular, when the SNR is 40dB, the proposed power allocation scheme has the outage probability of 0.0058, 0.0028 and 0.0013 for $\beta_1=2, \beta_2=2, \beta_1=2, \beta_2=4$, and $\beta_1=4, \beta_2=4$, respectively, whereas, the single carrier scheme has the relatively high outage probability of 0.0082.

That is, the outage probability of the proposed scheme is improved by 29.3%, 65.9%, and 84.1%, respectively, compared to the single carrier scheme.

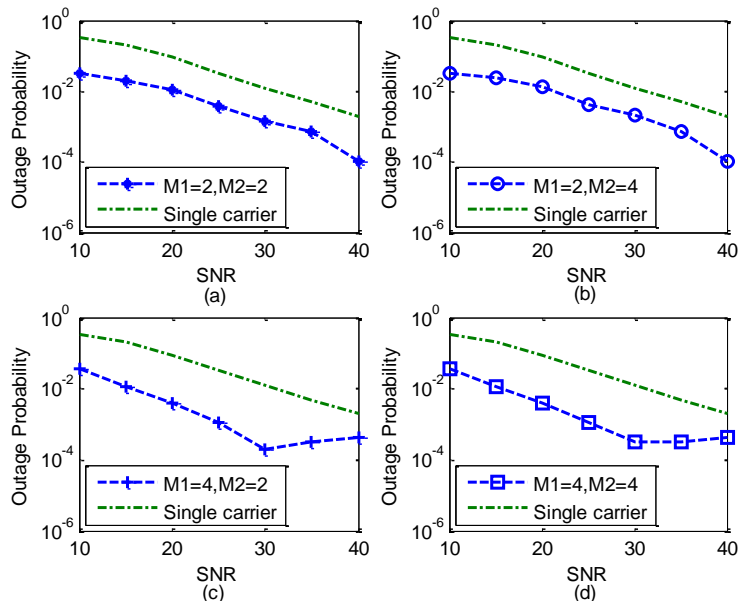


Figure 2. Outage Probability under different Number of sub-channels with $R=0.2R_{max}$

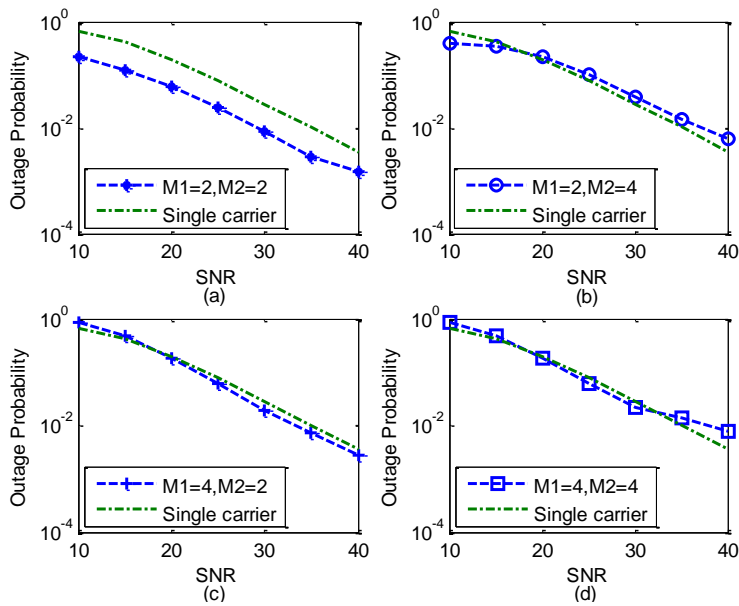


Figure 3. Outage Probability under different Number of Sub-channels with $R=0.6R_{max}$

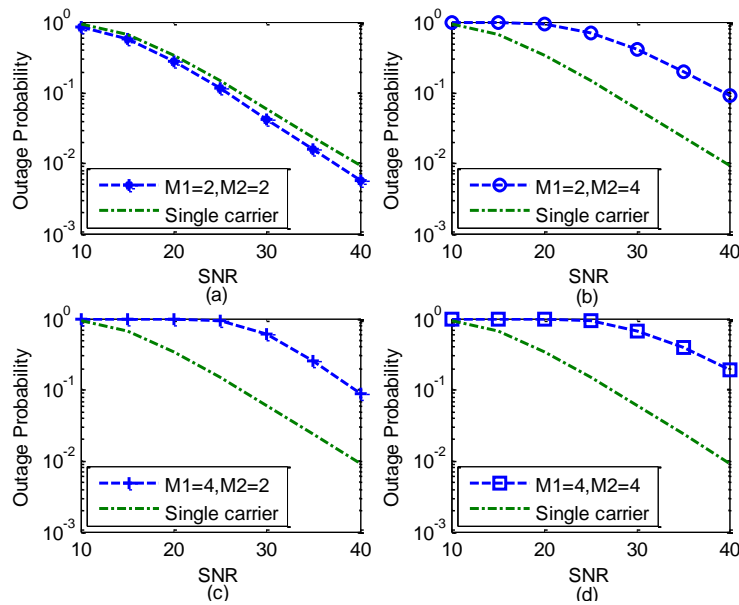


Figure 4. Outage Probability under different Number of Sub-channels with $R=R_{\max}$

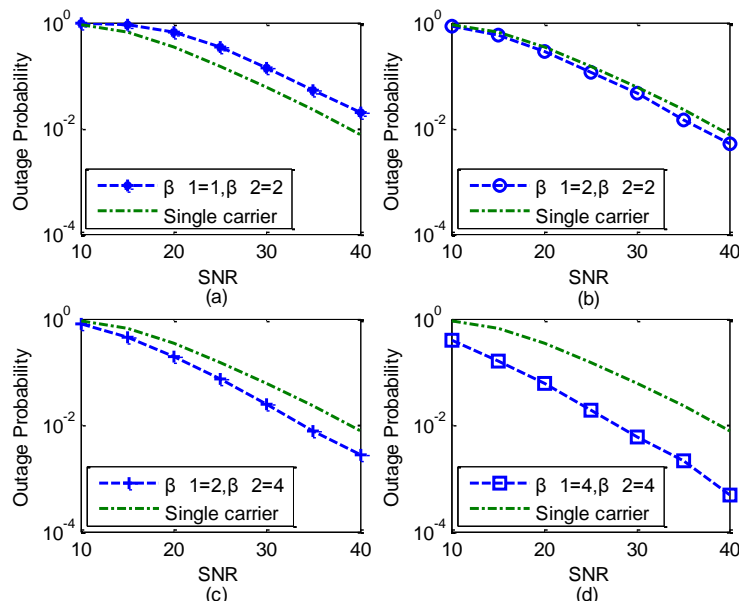


Figure 5. Outage Probability under different Channel Gain Ratio with $R=R_{\max}$

6. Conclusions

In this paper, we have investigated the decode-and-forward relay transmission in energy harvesting WSNs. Our object is to transmit and forward information from the source node with high reliability, by carefully power allocation among source-relay node pair, as well as the relay-destination node pair. We have conducted the simulations to evaluate the proposed power allocation scheme. The results show that the proposed scheme can significantly decrease the outage probability for threshold

targeted data rate, when the number of sub-channels for source-relay node pair is set to two, as well as the number of relay-destination node pair.

There might be some changing with the optimal number of sub-channels for source-relay node pair, as well as the number of relay-destination node pair, by varying the channel bandwidth. This is a promising future direction for effective power allocation and further performance improvement.

Acknowledgements

This work was partially supported by Nation Science Foundation of China (61661025, 61661026), and Key Laboratory of Photoelectricity Technology and Intelligent Control of Ministry of Education (Lanzhou Jiaotong University) (KFKT2016-2).

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