Wireless power transmission for remote-relay-nodes-aided smart metering

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Abstract: Wireless power transmission is a promising technique to provide continuous power supply for the limited capacitance of smart meters (SMs) with short distance communication. In this study, the authors propose a remote-relay-nodes (RRNs)-aided wireless SM system, where several geographically separated RRNs are connected to a concentrator or an acquire terminal via radio-over-fibre. A RRN selection scheme is employed in the wireless power transfer phase. With the energy harvested, the SM can report special or urgent events in the wireless information transfer phase. The asymptotic reporting probability and reliability of smart metering are derived in terms of close form over fading channels. Numerical results are provided to verify the theoretical analysis. The optimal deployment of RRNs can be also efficiently obtained by averaging the locations of a SM in the network.

1 Introduction

Reliable and efficient communication systems can provide bidirectional flow that smart grid relies on [1, 2]. As the nerve endings of smart grid, smart meters (SMs) can measure the energy usage in real time [3]. At present, various types of communication protocols have been employed to enable data exchange between SMs and the concentrator, which are mainly based on wire or wireless technologies [4]. Although wire communication can harness the benefits of the existing wiring, their installation is inflexible [5, 6]. For this reason, we investigate wireless smart metering system in this work.

The advent of new applications like power cut reporting and some other urgent events in smart metering system have proposed higher demand on SMs. Sometimes, a SM may not support sufficient time to report urgent events with its limited capacitance. Wireless power transmission is a promising technique to provide continuous power supply by enabling the SMs harvest the ambient radio frequency (RF) power and self-recharge their capacitance [7, 8]. Unfortunately, the efficiency of wireless power transmission is low due to the great path loss with long propagation [9]. Since the communication distance is short for wireless smart metering, it is feasible to implement the wireless power transmission technology in smart metering system.

In order to enhance the wireless power transmission efficiency, various types of communication system have been proposed. Distributed antenna system (DAS) is viewed as a network that can conquer the near-far effect [10]. The average distance between transmitters and receivers in DAS can be shortened, and the path loss can be mitigated [11]. The authors of [12] and [13] proposed a uniformly DAS with a large number of antennas. However, the models proposed are either inefficient for wireless power transmission or too complicated by connecting all the antennas to a base station. The most important thing is they are not applicable for smart metering system. Recently, the relay-aided wireless communication has attracted much attention in the area of smart grid communication [14]. To improve the information transmission rate, a relay station has been installed between the concentrator and the master station [15]. In [16], smart relays that can directionally forward the data to the desired concentrator have been put forward. The author of [17] has proposed a device-to-device (D2D)-aided relaying framework for energy management. In the state of art, there is little work on the simultaneous wireless power transmission and information transmission for smart metering system. Drawing support from the concepts of relay and DAS, this paper proposes a feasible wireless-powered based smart metering system.

In this paper, we study the wireless-powered-based smart metering with remote relay nodes (RRNs)-aided network. Firstly, a circle layout of radio-over-fibre (RoF) is proposed which can shorten the distance between SMs and RRNs. Besides, it is very convenient to connect all the RRNs via RoF. Secondly, the RRN with the maximum path loss is selected for the wireless power transfer to the target SM. Then, the asymptotic reporting probability and reliability are derived in the closed form. Numerical results are given to validate the theoretical analysis. In addition, the average reporting probability per SM in a cell is also evaluated by theoretical results, which efficiently obtain the optimal deployment of RRNs.

The rest of this paper is organised as follows. Section 2 introduces the RRNs-aided smart metering system model. In Section 3, the asymptotic reporting probability and reliability of smart metering are analysed. Numerical results are given in Section 4. Finally, Section 5 concludes this paper.

2 System model

We consider an RRNs-aided smart metering network, which consists of a concentrator with one antenna, M RRNs, and master station with network equipment and sever. The RRNs are geographically deployed across a circle link and they are connected to the concentrator via RoF, as shown in Fig. 1. When an urgent event occurs, a SM can harvest the ambient wireless power sent by RRNs and self-recharge its capacitance. Using the harvested energy, the SM reports this event to all the RRNs. Also then, RRNs forward information to the concentrator. At last, the concentrator can upload data collected to the master station through wireless communication system. In this work, we assume the channel state information is available at the receivers, and we also employ time division multiple access technique. Moreover, signals are supposed to experience frequency non-selective fading channels.

In a low-voltage transformer areas, let R_m be the mth RRN ($1 \leq m \leq M$), each SM and RRN has one omnidirectional antenna. The Rayleigh fading between R_m and the target SM for downlink and uplink transmission are denoted by h_m and g_m, respectively. The path loss between R_m and the target SM are denoted by L_m, where
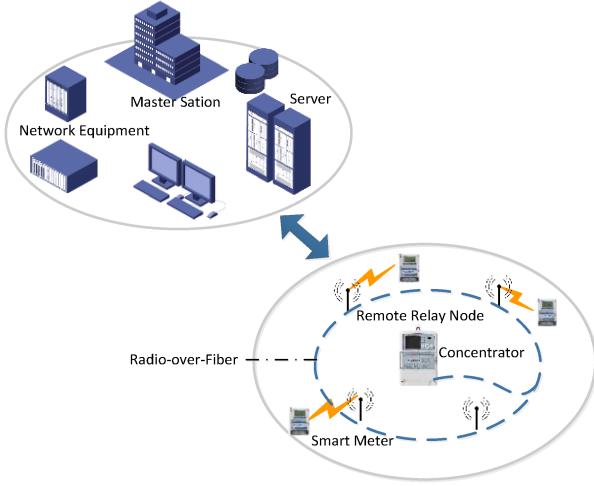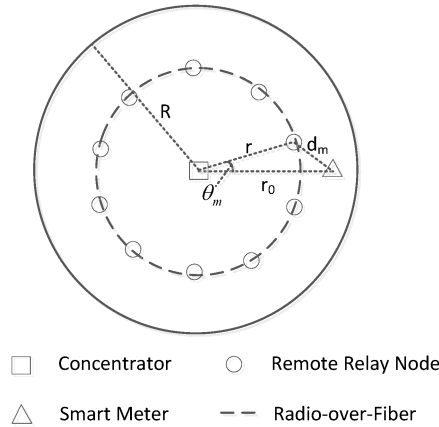
Fig. 1 *RRNs-aided smart metering system model*

Concentrator ☐ Remote Relay Node ○

Smart Meter △ Radio-over-Fiber — —

Fig. 2 *RRNs-aided network layout*

$L_m = d_m^{-\alpha}$, d_m is the distance from R_m to the target SM, and α is the path-loss exponent.

As shown in Fig. 2, the radius of a low-voltage transformer area is supposed to be R, RRNs are distributed across along a circle RoF link with radius r. Let r_0 be the distance between the cell centre and the target SM, and θ_m be the angle of r_0 and the direction from the cell centre to R_m. We assume $\theta_1 = 0$, then $\theta_m = 2\pi(m-1)/M$. Therefore, d_m can be derived as

$$d_m = \sqrt{r^2 + r_0^2 - 2rr_0\cos\theta_m} \tag{1}$$

With the harvest then forward protocol, each time block is divided into two periods. In the first period, τ, RRNs transmit RF signal to SMs. In the remaining period, SMs forward information to RRNs. The detailed transmission model is given below.

2.1 Wireless power transfer phase

In the first period, the target SM selects a RRN, R_0, based on the maximum path loss to receive RF energy, which is given by

$$L_o = \arg \max_{1 \le m \le M} \{L_m\} \tag{2}$$

The baseband signal sent by R_m is denoted by s_m $(E\{|s_m|^2\} = 1)$. During a time block, the received signal at the target SM is expressed as

$$r = \sqrt{P_t L_o} h_o s_o + n \tag{3}$$

where P_t is the transmit power of a RRN, n is the additive white Gaussian noise with mean zero and variance σ^2. Suppose P_t is

sufficiently large, the wireless power from the noise can be negligible. The energy harvested in τ at the SM receiver end is given by

$$Q = \tau\xi P_t L_o |h_o|^2 \tag{4}$$

where $0 < \xi < 1$ is the efficiency of energy conversion.

2.2 Wireless information transfer phase

In $1 - \tau$ period, the target SM transmits information to all the RRNs with the power harvested in the first period, and RRNs forward information to the concentrator. As the power harvested in the first period is used not only for information transmission but also for circuit operation, let η $(0 < \eta \le 1)$ be the fraction of power for information transmission. The power for reporting event in the second period by the target SM can be written as

$$P = \frac{\eta}{1 - \tau}Q \tag{5}$$

Define x_m as the transmitted signal form the target SM to R_m, where $E\{|x_m|^2\} = 1$. The received signal at the concentrator is obtained as

$$y = \sum_{m=1}^{M} \sqrt{P_m L_m} g_m x + n \tag{6}$$

where P_m is the transmitted power from the target SM to R_m which is controlled by the concentrator. The instantaneous signal-to-noise ratio (SNR) at the concentrator is derived as

$$\gamma = \frac{\sum_{m=1}^{M} P_m L_m |g_m|^2}{\sigma^2} \tag{7}$$

3 Reporting probability and reliability

As small cells are the features of 5G technology, massive RRNs can be deployed in a district to shorten the distance between receivers and transmitters. In this section, we aim to analyse the successful reporting probability and reliability of the target SM in the scenario of massive RRNs.

3.1 Reporting probability analysis

Theorem 1: We assume γ_T denotes the SNR threshold for outage communications. When the number of RRNs tends to be infinity, the asymptotic reporting probability is obtained as

$$P_{\text{RE}} \cong \exp\left\{-\frac{\gamma_T}{\lambda\bar{L}}\right\} \tag{8}$$

where $\lambda = (\tau/1 - \tau)(\eta\xi P_t L_o/\sigma^2)$. In (7), the average path loss, $\bar{L}$, is expressed as

$$\bar{L} = \lim_{M \to \infty} \frac{1}{M}\sum_{m=1}^{M} L_m \tag{9}$$

Proof: The successful reporting probability can be defined as

$$\begin{aligned} P_{\text{RE}} &= \Pr\{\gamma \ge \gamma_T\} \\ &= 1 - \Pr\left\{\lambda|h_o|^2 \sum_{m=1}^{M} L_m|g_m|^2 \le \gamma_T\right\} \end{aligned} \tag{10}$$

Let $\boldsymbol{g} = [g_1 \cdots g_M]^T$ be an $M \times 1$ vector. Then, $\boldsymbol{g}/\sqrt{M}$ is a random vector of identical and independent entries with zero mean and variance $1/M$. The eighth-order moment of the mth fading can be written as $E\{|g_m|^8\}/M^4$ with its order $\mathcal{O}(1/M^4)$. The $M \times M$
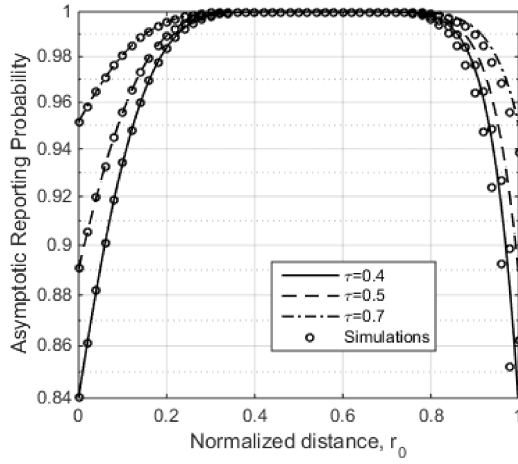
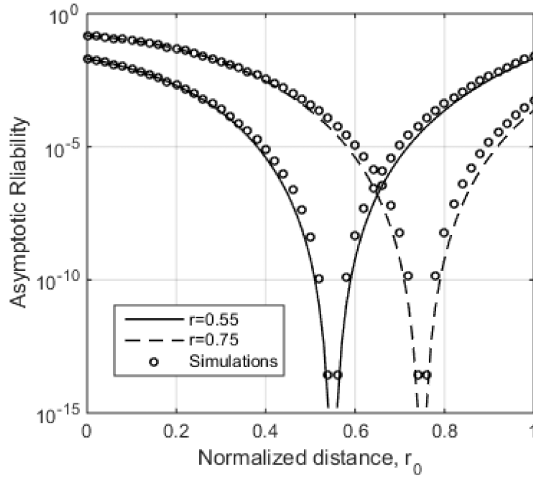**Fig. 3** *Asymptotic reporting probability versus normalised distance (r = 0.55)*

Fig. 4 *Asymptotic reliability versus normalised distance (τ = 0.5)*

diagonal matrix $L = \text{diag}\{L_1, \ldots, L_M\}$ is independent of $g/\sqrt{M}$. When M tends to be infinity, we have the following expression according [18]

$$\frac{1}{M}\sum_{m=1}^{M} L_m|g_m|^2 = \frac{1}{M}g^{\mathrm{H}}Lg \rightarrow M\sum_{m=1}^{M} L_m = \bar{L} \qquad (11)$$

Since h_o is the Rayleigh fading parameter, $|h_o|^2$ is exponential distributed. Substituting (11) to (10), we can derive the asymptotic reporting probability, as shown in (7). It is observed from (7) that the reporting probability is related with the deployment of RRNs, the time fraction of wireless power transfer and other preset factors □.

3.2 Reliability analysis

The reliability of smart grid communication can defined as the average error probability, which is given by $P_{e,c} = pQ(\sqrt{q\gamma})$, where p and q determine the modulation format. In this work, we employ binary shift keying modulation signals, i.e. $p = 1$ and $q = 2$. When the number of RRNs tends to be infinity, the asymptotic reliability of the target SM is obtained by using an alternative expression of Q function as

$$P_e = \int_0^\infty Q(\sqrt{2\gamma})f(\gamma)\mathrm{d}\gamma$$

$$= \frac{1}{\sqrt{2\pi}}\int_0^\infty e^{-\frac{t^2}{2}}F\left(\frac{t^2}{2}\right)\mathrm{d}t \qquad (12)$$

$$\cong \frac{1}{2} - \frac{1}{2}\sqrt{\frac{\lambda\bar{L}}{1 + \lambda\bar{L}}}$$

where $F(\cdot)$ denotes the cumulative distribution function of Rayleigh fading. In the derivation of (11), [19, eq. (3.321.3)] has been employed.

It is noted from (8) and (12) that both the reporting probability and reliability of the target SM communication are in proportion to the time fraction of wireless power transfer, τ. However, the transmission rate or the overall network throughput is not always in proportion to τ. If τ increases, the SM can harvest more power for information transmission in the uplink, therefore, higher throughput can be achieved. Nevertheless, the time for the information transmission tends to be shorten, which in turn decreases the whole network throughout. Since smart metering system is not sensitive to real-time communication, the time fraction is not the crucial research point in this work. On the other hand, the deployment of RRNs that determines the value of the average path loss can provide theoretical guideline for network design and implementation. The optimal deployment of RRNs can be efficiently calculated with the assistance of theoretical and numerical results.

4 Numerical results

In this section, numerical results are conducted to demonstrate the successful reporting probability and reliability of the target SM in RRNs-aided network, and the simulation results are presented to verify our theoretical expressions. Throughout this work, without stated otherwise, the cell radius is normalised by $R = 1.0$, the radius of RRNs is $r = 0.55$, the target SM locates at $r_0 = 0.75$ from the cell centre, the number of RRNs is $M = 6$, the path-loss exponent is 4.0, the efficiency of energy conversion is $\xi = 0.6$, the fraction of power for information transmission is $\eta = 0.8$, the time fraction for wireless power transfer is $\tau = 0.5$, the transmit power of each RAU is $P_t = 25$ dBm, the threshold of SNR is 3 dB, the carrier frequency is 2.5 GHz, and the small-scale fading is Rayleigh distributed.

Fig. 3 depicts the asymptotic reporting probability versus the normalised distance of the target SM with different time fraction of wireless power transfer. It is observed from Fig. 3 that the theoretical results can asymptotically agree with the simulation results. Higher reporting probability is gained when the target SM is installed around 0.4–0.8, whereas lower reporting probability is obtained when the target SM is installed at other locations. This is because when the SM locates near the RoF links, the distance between the SM and the selected RRN is shortened which mitigates the path loss. As a result, more energy can be harvested by the SM and higher gain of transmission can be achieved. It is also concluded from Fig. 3 that the successful reporting probability increases as more time is allocated to the wireless power transfer phase.

The asymptotic reliability of smart metering as a function of the normalised distance is plotted in Fig. 4. As expected, the theoretical results derived from (12) asymptotically match the simulation results, especially for small values of r_0. Since the derived theoretical expressions and simulation results have tight match, theoretical results can be employed to analyse the system performance. Besides, the best reliability performance is obtained at the locations of RRNs circle, i.e. $r_0 = 0.55$ and $r_0 = 0.75$, respectively.

In Fig. 5, we show the asymptotic reliability of smart metering for different number of RRNs. We set $\tau = 0.3, 0.5, 0.8$ for the wireless power transfer phase. It is can be seen from Fig. 5 that when $M \geq 30$, the reliability keeps a constant value for a fixed transmit power. We can infer that the theoretical results can agree well with the simulation results when $M \geq 30$. This also shows that in the circularly layout metering system with large number of

relays, the system reliability is determined by the total transmit power for a fixed M.

We assume all the SMs in a cell are randomly and uniformly distributed. The average reporting probability per SM that can indicate the average experience of SMs is shown in Fig. 6 for different values of RRNs radius and $M = 30$. We can see from Fig. 6 that the system performance degrades when installing RRNs around the centre or around the cell edge. In addition, we can see from Fig. 6 that the achievable average reporting probabilities for the case of $\tau = 0.3, 0.5, 0.8$ have similar behaviour with respect to the RRNs deployment. The optimal radius of RRNs is around $0.58R$. Thus, with the theoretical expressions, the optimal deployment of RRNs can be efficiently achieved without resorting to the time-consuming Monte Carlo simulations.

5 Conclusion

In this paper, we have investigated the asymptotic reporting probability and reliability performance in RRNs-aided smart metering network. A wireless power transmission based smart metering system has been proposed for short-range communications. To reduce the transmitted power, a maximised path loss based RRN selection method has been employed. The closed-form asymptotic reporting probability and reliability have been obtained over fading channels. Numerical and simulation results have been provided to reveal the impacts of key factors on the reporting probability and reliability. Moreover, the optimal deployment of RRNs has also been conducted through the average reporting probability per SM.

6 Acknowledgments

7 References

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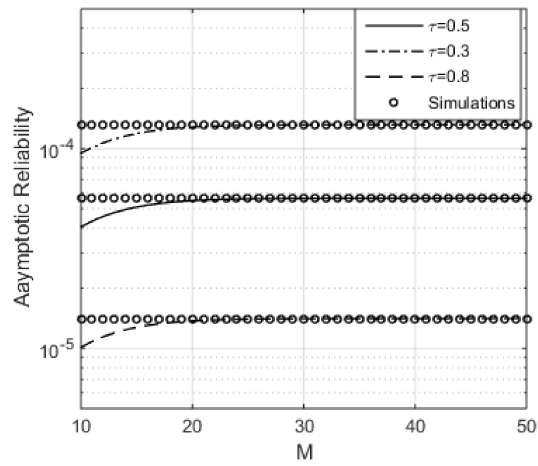
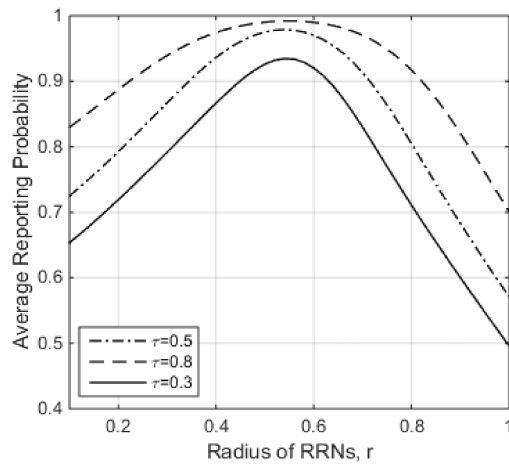**Fig. 5** *Asymptotic reliability versus the number of RRNs ($r_0 = 0.75$)*

Fig. 6 *Average reporting probability versus the radius of RRNs (M = 30)*