



Relay-Assisted Wireless Energy Transfer for Efficient Spectrum Sharing in Harsh Environments

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Abstract

With exponential growth in the number of wireless devices and limited available spectrum, the problem of spectrum sharing remains in forefront of the research community. Due to the large number of wireless sensing devices, even a small percentage of savings can translate into significant spectrum efficiencies. One of the main hurdles in efficient spectrum sharing in wireless sensor networks (WSN) is the problem of power management at the node level to promote longevity without polluting the spectrum, while promoting collaboration. This problem is even more challenging in extreme (harsh) environments where access to power and battery replacement and charging is limited, if not impossible. Passive sensor technology can be used to eliminate the need for batteries, but it suffers from short communication range. Recently, wireless energy transfer (WET) for powering remote sensor nodes in a WSN has drawn considerable research attention, since it can charge sensing circuits remotely and relieve the need for battery replacement. Modeling the charging and power utilization processes can help with smart transmission decisions, which can eliminate unnecessary transmissions and not only save limited battery power at the node level, but also efficiently utilize the shared spectrum. In this paper, we consider a general relay energy assisted scenario, where a transmitter is powered by an energy source through both direct and relay links. We model data and energy channels separately, transmit energy to power the transmitter battery and schedule data transmission based on stochastic models for data. We also consider various static, mobile and highly scattered channel models. We will set a threshold on required transmission energy and channel quality to decide whether the transmission can be successful (efficient use of spectrum) or the packet may not reach the destination (polluting the spectrum unnecessarily). An energy efficient scheduling method is proposed for the system model to determine whether to transmit data or stay silent based on the stored energy level and channel state. An analytical expression has been derived to approximate outage probability of the system in terms of energy and data thresholds. All theoretical results are validated by numerical simulations and verify the effectiveness of energy relaying and proposed energy efficient scheduling method in reducing the outage probability of the system

Keywords Spectrum sharing · Wireless sensor networks · Wireless energy transfer · Energy harvesting · Relay-assisted communications · Harsh environments

1 Introduction

Wirelessly powered communication networks have been proposed as a new method which takes advantage of both information and energy carried by radio signals [1]. Wireless energy transfer (WET) for powering sensor nodes in the wireless sensor networks (WSN) especially under extreme conditions, such as space applications and high temperature environments, has been attracting more and more interests recently from academics and industry [2, 3]. This involves the transmission of electrical energy without wires using time-varying electric, magnetic, or electromagnetic fields and has been demonstrated as a viable option for various

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communication systems [4, 5]. In addition, simultaneous wireless information and power transfer have been introduced as a sustainable solution for 5G wireless communications [6–8]. Energy harvesting has been recently developed as an efficient technique to minimize maintenance costs and extend lifetime of wireless networks [9]. It can help to have more efficient wireless networks where network nodes periodically harvest energy from energy sources in their surrounding environment [10]. Recent advances in WET and its possibility of sharing energy leads to the concept of energy cooperation [11].

Relay-assisted communication techniques have drawn tremendous research interest in recent decades [12–15]. This kind of communication is an efficient method for reliable data transmission, helps the severe propagation loss of wireless links and extends network coverage particularly in scenarios where source and destination are located far apart from one another. Their basic idea is allowing single-antenna devices to share their antennas and work collaboratively such that they construct a virtual MIMO system and create space diversity. As a result, the overall communication quality, including energy efficiency can be dramatically improved. The same concept applies to WET scenarios. The cooperation for energy transfer can be implemented to overcome the propagation attenuation caused by path-loss and channel fading. Energy-constrained relay node equipped with an energy harvesting device can harvest energy through the received RF signal from the source.

1.1 Related Works

The performance of cooperative networks aided by energy harvesting relay node in terms of outage behavior in slow fading scenario was investigated in [16]. The outage probability and the throughput of an amplify-and-forward relaying system using energy harvesting are analyzed in [17, 18]. Several power allocation strategies to optimize the outage probability in a decode-and-forward cooperative network where multiple source-destination pairs communicate via a shared energy harvesting relay is proposed in [19]. In [20], a harvest-then-cooperate protocol was proposed in a cooperative network where a source and amplify-and-forward based relay harvest energy from a hybrid access point in the downlink and cooperate in the uplink for the source information transmission. The approximate expression of the average throughput was derived for Rayleigh fading channels.

Orthogonal frequency division multiplexing (OFDM)-based wireless powered communication system is investigated in [21], where one user harvests energy from an energy access point (EAP) to power its information transmission to a data access point (DAP). The objective is to maximize the achievable rate at the DAP by jointly optimizing the sub-channel (SC) allocation over time, and

the power allocation over time and subchannels, for both WET and WIT links. Assuming availability of full channel state information, the structural results for the optimal SC/power allocation are obtained and an offline algorithm is proposed to solve the problem. Furthermore, we propose a low-complexity online algorithm when causal channel state information is available. Authors in [22] propose a design of wireless communication and wireless energy transfer system for underground wireless sensors and in-pipe robots. Acoustic waves are used for wireless energy transfer and LF (low frequency) and HF (high frequency) signals are used for wireless communications. Full-wave simulations are performed to study the wireless energy transfer and wireless communication performance.

Currently available off the shelf equipment provide continuous or periodic pulsed energy and data transmission which is not an ideal scheme due to the stochastic nature of wireless channels. Recently, a novel stochastic model for two separate data and energy channels and a new transmission scheduling were proposed in [23]. However, there is no work which studies outage probability performance of relay-assisted energy transmission scenario which in addition to direct link, energy harvesting relay helps energy source to power a transmitter which is attempting to send data to a destination based on energy efficient transmission scheduling.

In this paper, we model fading wireless channels for power and data separately and we transmit energy and data randomly based on two separate stochastic models for data and energy channels. We investigate the effects of energy efficient scheduling method on wireless sensors outage probability. This method can determine when to transmit data based on the stored energy level in the sensor and the noise levels on the data channel. If the sensor has a low level of energy and the data channel has a high level of noise it would be best to wait until either the sensor has more energy or the channel has less noise in order to avoid wasting energy and losing data. We consider Additive White Gaussian Noise (AWGN), Rayleigh and Rician channel models for static or mobile system nodes. We will set a threshold on required transmission energy and channel quality to decide whether the transmission is beneficial or risky and calculate the outage probability of the system. Outage probability of system including sensor energy and data outage and its relationship with energy and data threshold will be derived analytically and verified by simulations.

The rest of this paper is organized as follows. The proposed system model is presented in Sect. II. The protocol description and proposed energy efficient transmission scheduling method are discussed in Sect. III followed by analytical outage probability calculations in Sect. IV. Analytical derivations are verified by simulations in Sect. V and finally, the paper is concluded in Sect. VI.

2 System Model

Throughout this paper, we use subscript-S for source, subscript-T for transmitter, subscript-R for relay and subscript-D for destination. As shown in Fig. 1, this paper considers a WSN scenario that consists of four point to point channels including S-T, S-R, R-T and T-D pairs. The considered model transfers information from a transmitter terminal, T, to a destination terminal, D. We assume that the transmitter T is powered by an external energy source, S via direct link. Energy transferring process from the source S to the transmitter T is also assisted by a relay denoted by R. As a result, the transmitter T receives energy from two separate direct and relay links. All these devices are assumed to have only a single antenna in this paper. Let h_{XY} denote the channel coefficient from X to Y with $X, Y \in \{S, T, R, D\}$. Thus, the channel power gain from X to Y can be defined as $h_{XY} = |h_{XY}|^2$ which $|\cdot|$ denotes the absolute value operation [24]. We assume channel gains remain constant during each transmission block (denoted by T) but change independently from one block to another. Also, each transmission block is further divided into a number of time slots.

In this paper, we use the idea of modeling data and energy channels separately proposed in [23] and analyze adding relay-assisted energy transmission scenario. Depending on having static or mobile nodes, we consider three different channel models. For static channels where both nodes associated with one link are fixed, we consider AWGN channel model with a probability density function (PDF) of a normal distribution $f(x)$ as follows

$$f(x) = N(\mu, \sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(x-\mu)^2/2\sigma^2} \quad (1)$$

$$\sigma = \sqrt{10^{-\frac{SNR}{10}}} \quad (2)$$

where μ and σ are the mean and variance of an AWGN channel respectively and SNR denotes signal to noise ratio. In cases that we have relatively mobile nodes, we use Rayleigh

and Rician channel models in highly scattered environments without and with line of sight (LOS) with their PDFs as follows

$$g(y, \sigma^2) = \frac{y}{\sigma^2} e^{-\frac{y}{2\sigma^2}} \quad (3)$$

$$h(z, \sigma^2) = \frac{z}{\sigma^2} e^{-(z^2+v^2)/2\sigma^2} I_0\left(\frac{zv}{\sigma^2}\right) \quad (4)$$

where v is Rician channel parameter and $I_0()$ is the modified Bessel function with zeroth order. For simplicity in two cascaded channels calculations, we model $S \rightarrow R$ and $R \rightarrow T$ channels with AWGN channel model and study 9 different scenarios considering that $S \rightarrow T$ and $T \rightarrow D$ channels may fall under one of these three channel models.

3 Protocol Description and Proposed Energy Efficient Transmission Scheduling

As demonstrated in the system model section, our model consists of two transmission phases. In the first phase, which is providing energy for the transmitter T, the source S sends energy to the transmitter T over direct link. This can also be overheard by relay R due to the broadcasting nature of wireless communication. In addition, relay is assumed to have no other embedded energy supply or not willing to use its own energy for this communication. Thus, it needs to first harvest broadcasted energy by the source S, use portion of this energy for its own operation and then redirect remaining harvested energy toward the transmitter T. In the second phase, the powered transmitter T tries to send data to the destination D. The proposed relay-assisted transmission block in this paper is shown in Fig. 2. In each transmission block of time duration T , the first τT amount of time with $0 < \tau < 1$ is assigned to the energy transfer phase from the source S to the transmitter T and relay R. For simplicity of formulation, we follow a similar approach as [20] by selecting equal time slots for sending energy from the source S to the transmitter

Fig. 1 Relay-assisted energy charging model

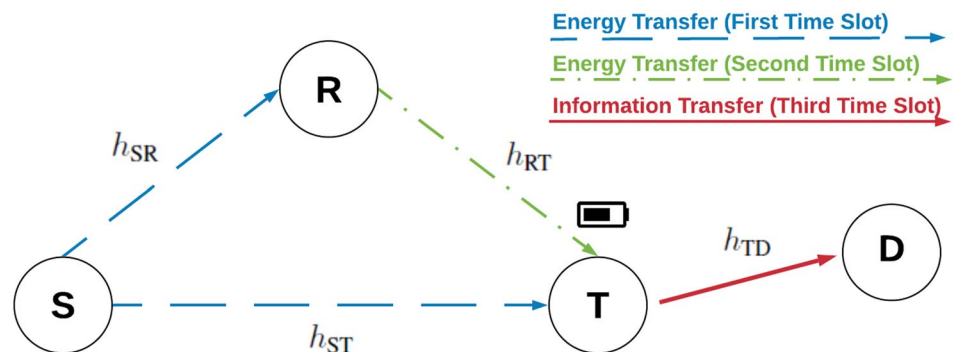
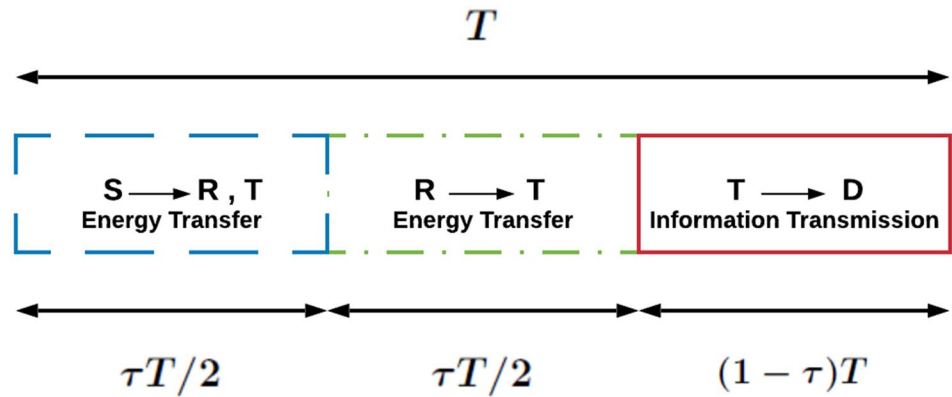


Fig. 2 Three time slot energy transfer and data communication



T and relay in the first time slot and from relay node to the transmitter T in the second time slot.

Thus, this fraction of the block is further divided into two time slots with an equal length of $\tau T/2$ as shown in Fig. 2. The remaining fraction $(1 - \tau)T$ of the block is for the second phase which is data transmission from the transmitter T to the destination D over the third time slot. We also assume that channel state does not change significantly from one time slot to the next and estimate the wireless channel status in each time slot and using that estimate for the next time slot.

In this paper, we use a decision algorithm as shown in Fig. 3 to avoid transmission of data when the channel is in low SNR or deep fading and battery energy is less than the minimum required energy for transmission. We set a threshold on energy and channel quality in the data transmission phase to decide whether the transmission in this time slot is beneficial or risky. This threshold is determined offline based on the channel model. It is obvious that outage can be significantly increased if the transmission is carried out

over the channel with SNR below the defined threshold. In the case that the transmitter T attempts to transmit data when data channel state is in poor quality state and battery level is very low, there is a very low chance that the destination receives transmitted data error free.

As a result, by this approach and avoiding risky transmission of data, we can decrease the outage probability of system and prevent wasting battery energy.

In the next sections, we will analyze outage probability expressions in the proposed system. We show that using the proposed relay-assisted energy transmission scheme for WET will decrease the outage probability of the system.

4 Analytical Outage Probability

4.1 Phase 1: Relay-Assisted Energy Transmission

Let P_S denote the transmission power of the source node S . We assume that this power is sufficiently large such that

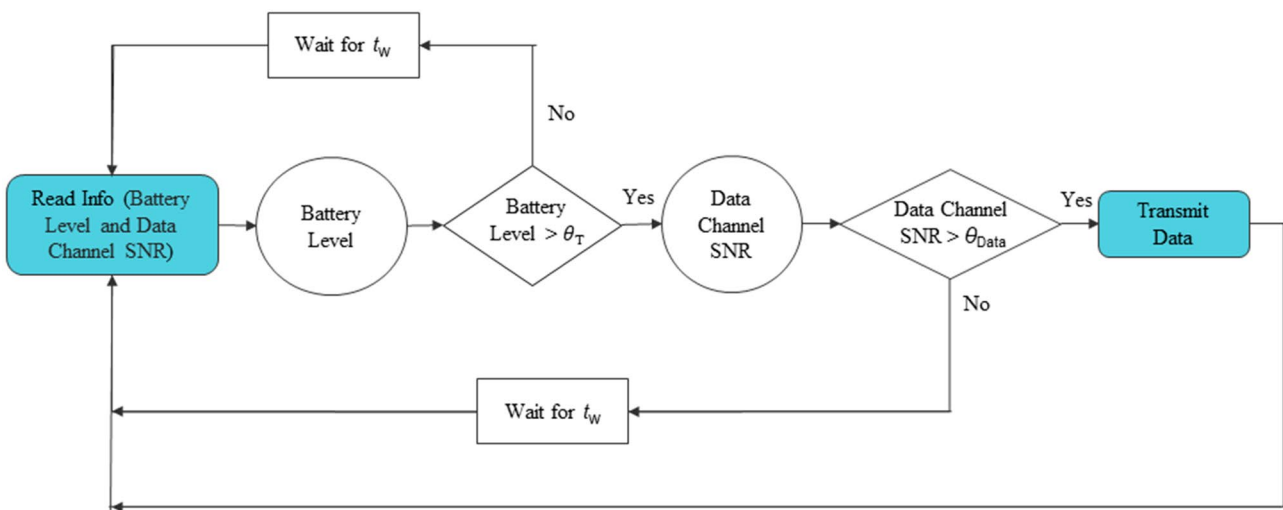


Fig. 3 Flowchart of the energy efficient scheduling method

the energy harvested from the noise is negligible. Also, P_R and P_T are transmission power of relay R and the transmitter T, respectively. In the first phase and first time slot, the transmitter S transmits energy through direct and relay channels. The energy of received signals by the transmitter T and relay R in the first time slot, denoted by superscription (1) in the following equations are

$$\mathbb{E}[||y_T^{(1)}||^2] = \mathbb{E}[||\sqrt{P_S}h_{ST}x_S^{(1)} + n_T||^2] \quad (5)$$

$$\mathbb{E}[||y_R^{(1)}||^2] = \mathbb{E}[||\sqrt{P_S}h_{SR}x_S^{(1)} + n_R||^2] \quad (6)$$

respectively, where $\mathbb{E}\{\cdot\}$ and $||\cdot||$ denote the expectation and L2-norm operations, $x_S^{(1)}$ is the signal generated from the transmitter S in the first time slot, while n_R and n_T are the AWGN at relay and the transmitter T, respectively. We assume that we have BPSK modulation at the input signal and as a result $E[||x_S^{(1)}||^2] = 1$.

Relay node is equipped with energy harvesting function to harvest received energy during the first time slot by power splitting. We assume that the source S has a fixed energy supply, while relay has no energy (or is not willing to spend its own energy) to help the source. Relay forwards energy harvested from the source. Let $\alpha \in [0, 1]$ denote the power splitting factor. More specifically, relay splits a portion of the received energy α for its operation and remaining $(1 - \alpha)$ for energy harvesting. The harvested energy at relay will be transferred to the transmitter T. Therefore, noting (1) in [20], the amount of energy harvested by relay R and the transmitter T during the first time slot can be expressed as

$$E_R^{(1)} = (1 - \alpha)\eta_R \frac{\tau T}{2} P_S h_{SR} \quad (7)$$

$$E_T^{(1)} = \eta_T \frac{\tau T}{2} P_S h_{ST} \quad (8)$$

where η_R and η_T are the energy harvesting efficiency at relay and the transmitter nodes. The transmitted relay power is thus given by

$$P_R = \frac{E_R^{(1)}}{\frac{\tau T}{2}} = (1 - \alpha)\eta_R P_S h_{SR} \quad (9)$$

Hence, the received energy at the transmitter T by relay R in the second time slot, denoted by superscription (2) in the following equation, can be written as

$$\mathbb{E}[||y_T^{(2)}||^2] = \mathbb{E}[||\sqrt{P_R}h_{RT}y_R^{(1)} + n_T||^2] \quad (10)$$

In case the received energy at relay R is less than the amount needed for its own operation, relay will not forward any

energy to transmitter T, during the first time slot. Since $S \rightarrow R$ power channel is modeled using AWGN channel, energy outage at relay node can be written as follows

$$\begin{aligned} P_R^E &= \Pr(\text{outage at relay}) = \Pr(X_R^{(1)} \leq \theta_R) \\ &= \int_{-\infty}^{\theta_R} N(\mu_{SR}, \sigma_{SR}^2) dx \\ &= \frac{1}{2} \left[1 + \text{erf}\left(\frac{\theta_R - \mu_{SR}}{\sigma_{SR} \sqrt{2}}\right) \right] \end{aligned} \quad (11)$$

where $\Pr(\cdot)$ denotes probability, $X_R^{(1)}$ is a random variable representing received energy at relay node over first time slot, $\mu_{SR} = 1$, θ_R is required energy for relay to operate and $\text{erf}(\cdot)$ is the Gaussian error function. According to (2), σ_{SR}^2 in this equation depends on SNR of $S \rightarrow R$ channel which is

$$\gamma_{SR} = \frac{\alpha \eta_R P_S h_{SR}}{N_0} \quad (12)$$

where N_0 is power spectrum of the white noise and α is the portion of the energy used by relay as defined before. Similarly, SNR of $S \rightarrow T$ and $R \rightarrow T$ channels are

$$\gamma_{ST} = \frac{\eta_T P_S h_{ST}}{N_0} \quad (13)$$

$$\gamma_{RT} = \frac{\eta_T P_R h_{RT}}{N_0} \quad (14)$$

where P_R is derived in (9).

If we do not have outage at relay node, in the second phase and the third time slot when the transmitter T attempts to send data to the destination D, the outage probability is defined for the case when the total received energy at the transmitter T through direct and relay links over the first and second time slots is less than the required transmit power threshold θ_T at the transmitter. Let $X_{ST}^{(1)}$, $X_{SR}^{(1)}$, $X_{RT}^{(2)}$, $X_{SRT}^{(1,2)}$, $X_T^{(1)}$ and $X_T^{(1,2)}$ denote random variables representing received energy which subscripts and superscripts represent channel names and time slots. Since total energy received at the transmitter T is equal to the sum of energy received by relay and direct links during the first and second time slots, its PDF can be calculated by convolution of direct and relay channels PDFs as follows

$$f_{X_T^{(1,2)}}(x) = f_{X_{ST}^{(1)}}(x) * f_{X_{SRT}^{(1,2)}}(x) \quad (15)$$

For simplicity in two cascaded channels PDF calculations, we assume that $S \rightarrow R$ and $R \rightarrow T$ channels are modeled using AWGN-AWGN channel models, respectively. The PDF of relay channel over the first and second time slots can be calculated as follows

$$f_{X_{\text{SRT}}^{(1),(2)}}(x) = f_{X_{\text{SR}}^{(1)}}(x) * f_{X_{\text{RT}}^{(2)}}(x) \\ = N(\mu_{\text{SRT}}, \sigma_{\text{SRT}}^2) \quad (16)$$

where $\mu_{\text{SRT}} = \mu_{\text{SR}} + \mu_{\text{RT}}$, $\sigma_{\text{SRT}}^2 = \sigma_{\text{SR}}^2 + \sigma_{\text{RT}}^2$ and σ_{RT}^2 depends on instantaneous SNR of R $\rightarrow$ T channel which is defined by (14). For the case when the S $\rightarrow$ T energy channel is modeled using Rician channel model, the PDF of total energy received by the transmitter T resulting from relay and direct links can be calculated using (1), (4), (15) and (16):

$$f_{X_{\text{T}}^{(1),(2)}}(x) = N(\mu_{\text{SRT}}, \sigma_{\text{SRT}}^2) * h(x, \sigma_{\text{ST}}^2) \\ = \frac{1}{\sqrt{2\pi\sigma_{\text{SRT}}^2}} e^{-(x-\mu_{\text{SRT}})^2/2\sigma_{\text{SRT}}^2} \\ * \left(\frac{x}{\sigma_{\text{ST}}^2} e^{-(x^2+v^2)/2\sigma_{\text{ST}}^2} I_0\left(\frac{xv}{\sigma_{\text{ST}}^2}\right) \right) \quad (17)$$

where σ_{ST}^2 depends on instantaneous SNR of S $\rightarrow$ T channel which is defined by (13). Outage probability is the probability that the received energy is less than the energy required to transmit. As a result, the outage probability when relay assists in energy transmission can be calculated using (17) as follows

$$\triangle \\ P_{\text{T}}^{\text{E}} = \Pr(\text{energy outage with relay}) = \Pr(X_{\text{T}}^{(1),(2)} \leq \theta_{\text{T}}) \\ = \int_{-\infty}^{\theta_{\text{T}}} f_{X_{\text{T}}^{(1),(2)}}(x) dx \quad (18)$$

where θ_{T} is the minimum required transmit energy at the transmitter T for data transmission. In the special case when there is an outage at relay node, the transmitter T only receives energy from direct channel S $\rightarrow$ T over the first time slot and by using (4), energy outage probability in this case is

$$\bar{-} \\ P_{\text{T}}^{\text{E}} = \Pr(\text{energy outage w/o relay}) = \Pr(X_{\text{T}}^{(1)} \leq \theta_{\text{T}}) \\ = \int_{-\infty}^{\theta_{\text{T}}} h(x, \sigma_{\text{ST}}^2) dx \quad (19)$$

4.2 Phase 2: Data Transmission

In the phase 2, the transmitter T transmits data through the direct link to the destination D in the third time slot. The transmitter power is supplied through direct and relay links in the first and second time slots. We assume that the transmitter T has fixed energy for its operation and the total harvested energy over two time slots will be stored in its battery and be used for data transmission in the third time slot. Harvested energy by the transmitter T over the first and second time slots by using (8), can be written as follows

$$E_{\text{T}}^{(1),(2)} = E_{\text{T}}^{(1)} + E_{\text{T}}^{(2)} = \eta_{\text{T}} \frac{\tau T}{2} P_{\text{S}} h_{\text{ST}} + \eta_{\text{T}} \frac{\tau T}{2} P_{\text{R}} h_{\text{RT}} \quad (20)$$

As a result, the data transmission power of the transmitter in the relay-assisted scenario where there is no outage at relay node can be expressed as follows

$$P_{\text{T}}^{\text{Relay Assisted}} = \frac{E_{\text{T}}^{(1),(2)}}{(1-\tau)T} \quad (21)$$

Thus, the energy of received signal by the destination D in the third time slot, denoted by superscription (3) in the following equation, can be written as

$$\mathbb{E}[\|y_{\text{D}}^{(3)}\|^2] = \mathbb{E}[\|\sqrt{P_{\text{T}}} h_{\text{TD}} x_{\text{T}}^{(3)} + n_{\text{D}}\|^2] \quad (22)$$

where $x_{\text{T}}^{(3)}$ is the signal generated from the transmitter T in the third time slot, while n_{D} is the AWGN at the destination D and P_{T} is the transmission power of the transmitter T.

Data outage happens when the noise on the data channel is more than defined threshold θ_{Data} . For the case when T $\rightarrow$ D data channel is modeled using a Rayleigh channel model, data outage in the relay-assisted scenario can be approximated as follows by using (3)

$$\triangle \\ P_{\text{T}}^{\text{D}} = \Pr(\text{data outage with relay}) = \Pr(X_{\text{D}}^{(3)} \leq \theta_{\text{Data}}) \\ = \int_{-\infty}^{\theta_{\text{Data}}} \frac{y}{\sigma_{\text{TD}}^2} e^{-\frac{y}{2\sigma_{\text{TD}}^2}} dy \quad (23)$$

where $X_{\text{D}}^{(3)}$ is a random variable representing data received at the destination node D over the third time slot, θ_{Data} is data channel threshold and σ_{TD}^2 depends on SNR of T $\rightarrow$ D channel which is

$$\gamma_{\text{TD}} = \frac{P_{\text{T}}^{\text{Relay Assisted}} h_{\text{TD}}}{N_0} \quad (24)$$

and $P_{\text{T}}^{\text{Relay Assisted}}$ is derived in (21). In case which there is outage at relay node, data outage in direct energy transmission scenario without having relay $P_{\text{T}}^{\text{D}} = \Pr(\text{data outage w/o relay})$, can be calculated using (23) and (24) by replacing data transmission power as following using (8)

$$P_{\text{T}}^{\text{Direct}} = \frac{E_{\text{T}}^{(1)}}{(1-\tau)T} \quad (25)$$

4.3 Outage Probability of System

Since the power and data channels are independent, the probability of an outage occurring in the proposed relay-assisted scenario is as follows

$\Pr(\text{system outage}) =$

$$(P_R^E) \times \left[P_T^E + (1 - P_T^E) \times (P_T^D) \right] + (1 - P_R^E) \times \left[P_T^E + (1 - P_T^E) \times (P_T^D) \right] \quad (26)$$

which can be calculated using (11), (18), (19) and (23). In this paper, we assumed that $S \rightarrow R$ and $R \rightarrow T$ channels are modeled using AWGN channel model and $S \rightarrow T$ and $T \rightarrow D$ channels may fall under one of three channel models. Based on that, we will have 9 different channel model combinations. We derived outage probability for the case that we have AWGN-AWGN-Rician-Rayleigh channels for $S \rightarrow R$, $R \rightarrow T$, $S \rightarrow T$ and $T \rightarrow D$ links respectively and will consider other possible scenarios in simulation part. The existing integrals in equations can be evaluated numerically to provide outage probability of system. Analytical results are verified by simulations in the next section.

5 Simulation Results

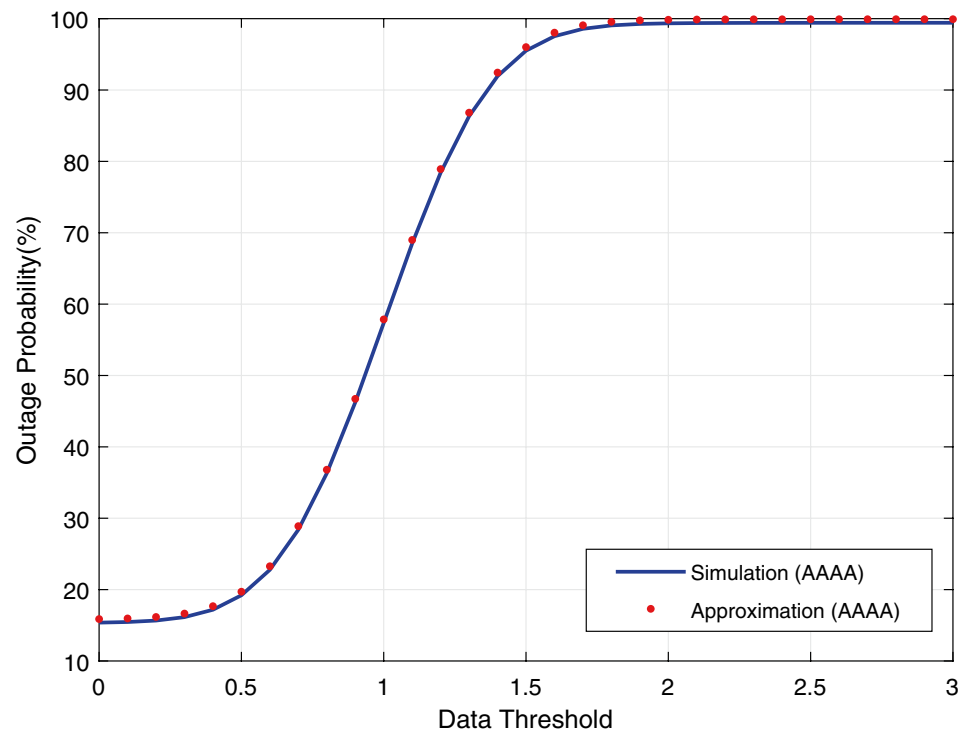
Simulations are conducted using MATLAB to verify the analytical calculations for various energy and data channel model combinations using AWGN, Rayleigh, and Rician models. In all simulation figures, the channel names correspond to the $S \rightarrow R$, $R \rightarrow T$, $S \rightarrow T$ and $T \rightarrow D$ channels

and abbreviations A, R and C indicate AWGN, Rayleigh and Rician channels, respectively.

The outage versus the data threshold with the inclusion of proposed relay-assisted energy transmission scenario is represented in Fig. 4. This figure compares the calculated system outage in (26) with simulations and shows the accuracy of our calculations. When the data threshold is low, the sensor never transmits and therefore never uses energy and it will result in data outage of zero percent and conversely, when the system has a high data threshold the sensor will transmit at every time slot resulting in a maximum data outage probability and consequently system outage probability. For a desired outage level and design criteria, an appropriate threshold may be chosen using this graph. From a practical point of view, it is of value to be able to calculate system outage based on data threshold. It might not be possible to choose the environment the system is in, but we can choose a data threshold to maximize the number of successful transmissions and minimize the outage.

Figure 5 compares the outage probability of our proposed relay-assisted energy transmission scenario with the case that there is only energy transmission over the direct link without having any relay versus data threshold. As we can see from this figure, in the proposed relay-assisted scenario the system outage is decreasing significantly which shows the effectiveness of the proposed scheme in this paper. Also, we simulate the outage probability in periodic transmission method represented in literature and as we can see our

Fig. 4 Analytically calculated outage vs data threshold verified by simulation for proposed relay-assisted scheme. All channels are modeled using AWGN model denoted by AAAA



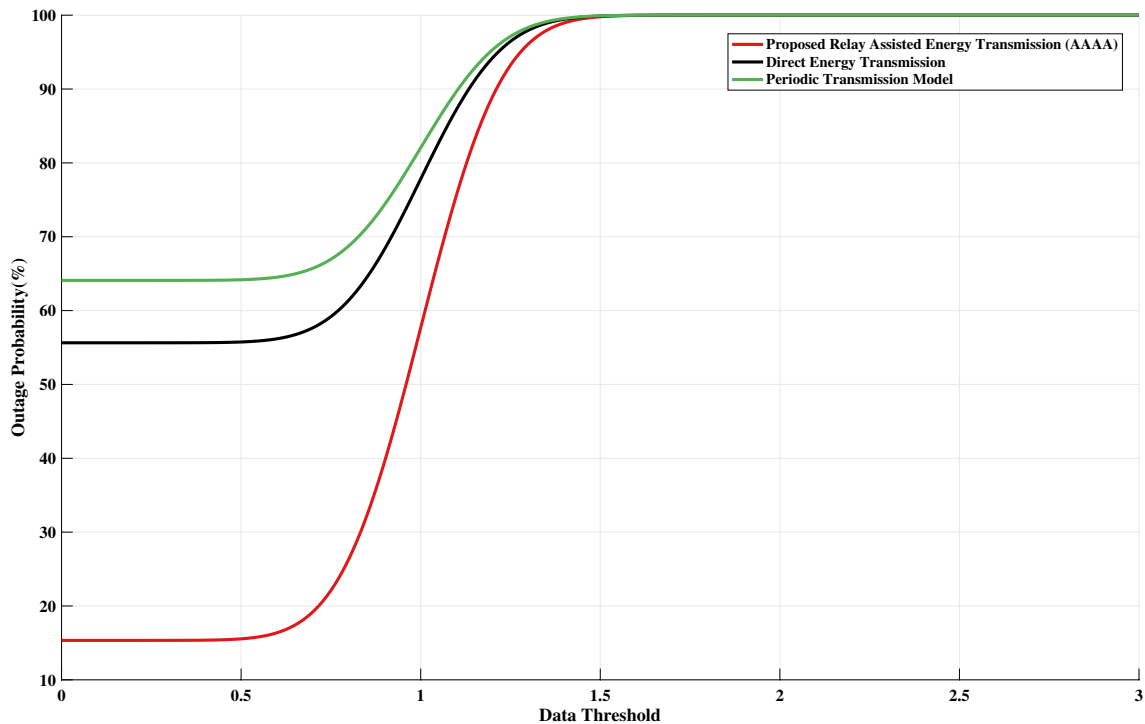


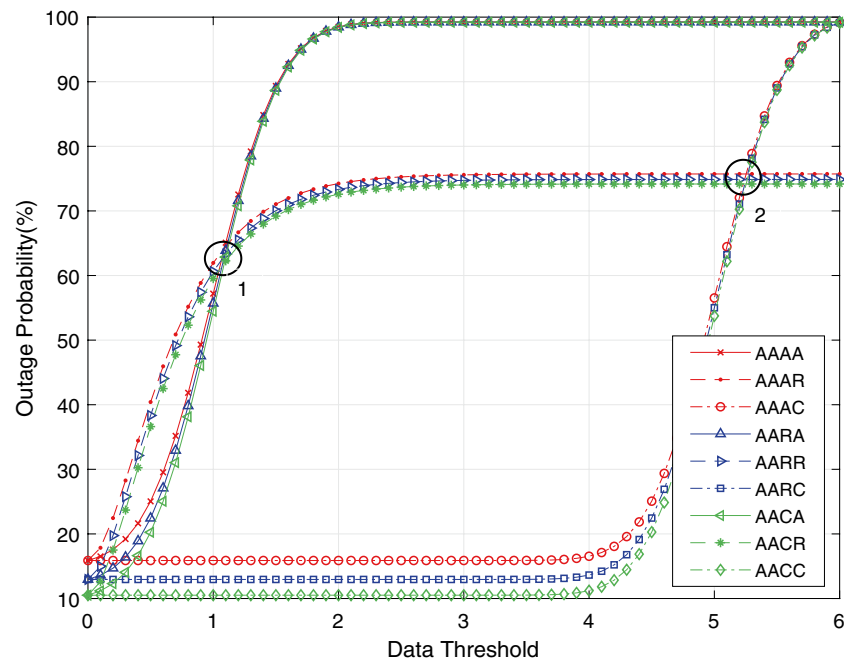
Fig. 5 Proposed relay-assisted system outage compared to periodic transmission method proposed in literature and direct energy transmission with no relay for AWGN model for all channels denoted by AAAA

proposed method has much less outage probability which shows the effectiveness of our model.

The system outage versus data threshold in all possible channel model combinations is represented in Fig. 6 which there are two crossover points. As we can see, for data

thresholds less than first crossover point, the best outage probability performance is for the channel combinations that there are Rician channel and the worst is for Rayleigh channel model at $T \rightarrow D$. Between the first and second crossover points, the best performance is for Rician and the worst is

Fig. 6 System outage probability for various energy and data channels. Channel names correspond to the $S \rightarrow R$, $R \rightarrow T$, $S \rightarrow T$ and $T \rightarrow D$ channels and abbreviations A, R and C indicate AWGN, Rayleigh and Rician channels, respectively



for AWGN and after second crossover point the best performance is for the Rayleigh and the worst is for the AWGN channel at $T \rightarrow D$.

6 Conclusion

Wireless energy transfer technology has recently drawn significant attention since it can solve battery replacement problem of conventional battery powered wireless sensor boards and limited communication range of passive battery free sensors. In this paper, another dimension of this emerging technology that can significantly impact efficient spectrum sharing is presented. Relay-assisted energy transfer concept combined by intelligent scheduling of transmissions based on available power and channel conditions has been shown to improve our efficiency in accessing spectrum and minimizing power consumption. In this paper, we proposed and analyzed a relay-assisted energy transmission scenario and modelled data and energy channels, separately. Various static, mobile, highly scattered without and with LOS channel models are all studied. Energy efficient transmission scheduling for the data channel was shown reduce outage probability, save on power, and minimize unnecessary spectrum access by avoiding transmitting data on a noisy channel or when the transmitter does not have enough power to successfully transmit data. Outage probability of system including sensor energy outage (running out of energy) and data outage and its relationship with a threshold (when to transmit based on channel condition) was derived analytically and verified by simulations. In addition, we can see from simulation results that proposed relay-assisted energy transmission scheme can decrease the outage probability of the system. Future research can include study of a scaled up network to develop new methods at the network level and further improving the proposed concept.

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