IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received December 8, 2016, accepted January 1, 2017, date of publication January 24, 2017, date of current version July 31, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2657551

Performance Characterization of Machine-to-Machine Networks With Energy Harvesting and Social-Aware Relays

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This work was supported in part by the National Natural Science Foundation of China under Grant 61525101, Grant 61227801, and Grant 61601055 and in part by the National Key Technology R&D Program of China under Grant 2015ZX03002008-008.

ABSTRACT In this paper, we propose a large-scale machine-to-machine (M2M) network architecture that incorporates energy harvesting and social-aware relays. The relay is powered by harvesting radio frequency energy and adopts the simultaneous wireless information and power transfer strategy. For the social aspect, a relay is conversant with only some of the communities and will only assist the data transfer of conversant sources. Moreover, for the energy harvesting and social-aware relay that assists the cooperative transmission protocol, we propose two different relay selection strategies, that is, *social-aware random relay selection* and *social-aware best relay selection*. The outage probability and network throughput of the proposed protocols are derived in a closed form using the stochastic geometry model, where the multiple M2M transmitter–receiver pairs and relays form independent homogeneous Poisson point processes, respectively. By comparing with the situation without social awareness, we find that social awareness can improve performance in some situations. The theoretical analysis is validated by extensive simulations.

INDEX TERMS Cooperative network, energy harvesting, relay selection strategies, social networking characteristics, stochastic geometry.

I. INTRODUCTION

Machine to machine (M2M)communication networks are envisioned to be widely deployed for environment monitoring, industry production automation, and smart housing. Ericsson predicts that there will be about 15 billion M2M devices in 2021 and most of them will be low-power devices with short-range communication [1]. In practice, it is in general difficult for the signal transmitted by the low-power device to reach the destination due to long propagation path or shadowing [2]. Cooperative relaying techniques can mitigate the attenuation and extend the coverage of communication. Therefore, many devices are deployed to cooperate as relays in the M2M communication networks recently.

However, supplying power to numerous distributed relays and maintaining their operations bring huge challenge to existing systems. As for energy supply, energy harvesting through wireless radio frequency (RF) is promising in generating small amount of convenient electrical power for wireless devices [3], [4]. Since wireless signal can transport information as well as energy, simultaneously wireless information and power transfer (SWIPT) [5] strategies enable relays to perform energy harvesting and information gathering from the same signal radiated by the source. Therefore, energy harvesting technologies are well suited for relay assisted cooperative M2M communications as it can reduce the deployment cost.

Moreover, relays are deployed by different entities and are utilized by different users in practice. The social networking characteristics lead them to have different priorities or preferences for different networks [6]. The relaying link of the M2M communication may be intermittent due to the fact that the selected user may be reluctant to cooperate as relays that assist the communication of the unknown sources, resulting in low quality of service [7]. Therefore, taking social networking characteristic into M2M network to enhance the network performance is a growing trend. Consequently, M2M cooperation and the relay selection strategies should be appropriately designed with social awareness in order to actualize resource utilization efficiently.

In this paper, we propose a large-scale M2M network architecture with energy harvesting and social-aware relays. The proposed architecture consists of two domains, namely, energy assisted physical domain and social domain. In the energy assisted physical domain, a large-scale network overlaid with multiple co-existing communities is studied using a stochastic geometry model where M2M transmitter-receiver pairs and relays form independent homogeneous Poisson point processes (HPPPs), respectively. The social domain illustrates the social relationships and defines that a relay is conversant with some communities and will only assist the data transfer of conversant sources. On these bases, an energy harvesting and social-aware relay assisted cooperative transmission protocol is proposed with two different relay selection strategies, namely, *social-aware random relay selection* (SRRS) and *social-aware best relay selection* (SBRS). We derive the outage probability and network throughput in a closed-form and show that the social awareness can improve the stability of the communication. Moreover, extensive simulations are conducted to validate the theoretical analysis.

A. RELATED WORK

To support a large number of distributed devices, M2M system needs to be energy efficient. Energy harvesting from ambient RF signals which can prolong the operation of battery-equipped devices is particularly suitable for M2M networks. The devices conduct energy harvesting via the SWIPT strategy which dually utilizes RF signal for information reception. The idea of SWIPT is first proposed by Varshney in [8], and the tradeoff between energy harvesting and information transmission over one single noisy channel is characterized. Since the receiver cannot share the same portion of signal energy for both harvesting energy and extracting information, a more practical SWIPT protocol named on-off power splitting protocol for a point-to-point link is proposed in [9], which splits the received signal for energy harvesting and information processing with an adjustable power level.

Cooperative relaying techniques can improve network coverage and are fully compatible with the SWIPT protocol. In [10], a power splitting based relaying protocol and a time switching based relaying protocol are investigated to enable information decoding and energy harvesting at the relay node in wireless amplifying and forwarding relay networks. SWIPT in an orthogonal frequency division multiplexing (OFDM) relaying system is considered in [11], where a source transmits energy and information simultaneously to a relay and a relay retransmits the information to the destination with a power splitting based relaying protocol.

However, the aforementioned literatures only consider SWIPT for a single source-destination pair. SWIPT for large scale networks with multiple source-destination pairs is more complex and practical as the interference among devices needs to be considered. Huang *et al.* [13] investigated the throughput of a large-scale mobile ad-hoc network powered by energy harvesting. A hybrid network consisting of randomly deployed power beacons is analyzed with an outage constraint, and the trade-off between the power beacon density and the network throughput is characterized [13]. Lee *et al.* [14] studied opportunistic wireless energy harvesting in cognitive radio networks, where secondary transmitters not only utilize spectrum opportunity for data transmission, but also search for active primary users to harvest RF energy. Moreover, the locations of nodes are modeled by HPPPs.

However, there are some limitations in the aforementioned work. First, most existing work only considers point-to-point or point-to-multi-point cooperative network configurations. Very few studies focus on RF energy harvesting in large-scale networks with randomly distributed relays. Second, in relay assisted cooperative systems, the locations of the relays and the distances between every two nodes are restricted, e.g., Lee *et al.* [14] assume that the distance between the relay and the destination is a constant value, and the relay is located on a line between the source and destination in . Third, the interference that can be considered as renewable source for energy harvesting is ignored in previous literatures.

Recently, social networks have gained wide attention and many researchers have exploited social networking characteristics to promote the performance of wireless networks. Social graph is a convenient tool to illustrate the relationship between two nodes. Neighbor graph is utilized in [15] to represent the encounter history of nodes and connectivity graph is a popular solution to quantify the relationships among devices by observing their contact time [16], [17]. Wang *et al.* [18] presented a novel graph theoretical framework for resource allocation by exploiting the inherent interplay between social networks and wireless communications. Moreover, Zhang *et al.* [19] defined and employed user social patterns in LTE-advanced networks to promote network performance.

For social-aware cooperative transmission, the cooperation among socially related users can be promoted by employing the social-aware relay selection. The preferences of the users for relaying could acquire channel access and reduce the privacy concerns of relaying, establishing trustworthy cooperative M2M networks. Datsika *et al.* [5] proposed a social-aware cooperative device-to-device (D2D) protocol that promotes the use of friendly users as relay and they also proved that exploiting social awareness can reduce the energy consumption of cooperative communication. Zhang *et al.* [20] designed a social trust based cooperative D2D relaying framework and derived an optimal social-aware relay selection strategy by utilizing the proposed relay probing scheme, which can differentiate users with regard to both the physical distance and social trust level. Moreover, Chen *et al.* [21] investigated social awareness including social trust and social reciprocity to enhance cooperative

D2D communications, where devices serve as relays for each other.

As discussed above, most existing literatures do not take social networking characteristics into account. While there are some studies about user social patterns in wireless networks, they did not combine social networking characteristics and energy harvesting techniques.

B. SUMMARY AND ORGANIZATION

The main contributions are summarized as follows:

1) Energy harvesting technologies and social networking characteristics are studied for cooperative M2M networks to form a large-scale network architecture with relays. The proposed architecture consists of two domains, that is, the energy assisted physical domain and the social domain.
2) An energy harvesting and social-aware relay that assists cooperative transmission protocol is proposed with SRRS and SBRS strategies. We derive the close-formed outage probability and network throughput for proposed transmissions.
3) We evaluate and simulate the performance of the proposed cooperative transmission protocols with SRRS and SBRS under different parameter settings. Numerical results show that social awareness can improve network performance.

The remainder of this paper is organized as follows. The social-aware energy harvesting M2M architecture, transmission mode and performance metrics are introduced in Section II. Section III formulates the performance analysis for the proposed transmission protocols with SRRS and SBRS strategies. Section VI presents the numerical results and Section V concludes the paper.

II. SYSTEM MODEL

A. SOCIAL-AWARE ENERGY HARVESTING M2M ARCHITECTURE

The architecture of the social-aware energy harvesting M2M network is illustrated in Fig. 1, which consists of two domains, i.e., the social domain and the energy assisted physical domain. Devices in the physical domain may refer to portable wireless devices, which are carried by users belonging to different communities. The social domain illustrates the social relationships among these devices. The following introduces the domains and functions of components in detail.

In the social domain, community is a key component that models a group of users with stable and close social relationships. This is because the users in the same community behave with the same preference and always contact each other frequently. Since the social networking characteristics such as social-tie quantifies the strength of the social connection among users, we assume the users in the same community have strong social-ties. In this paper, all the source-destination pairs are divided into K co-existing communities according to their social preferences. The social relationships among the distributed relays and the sources are

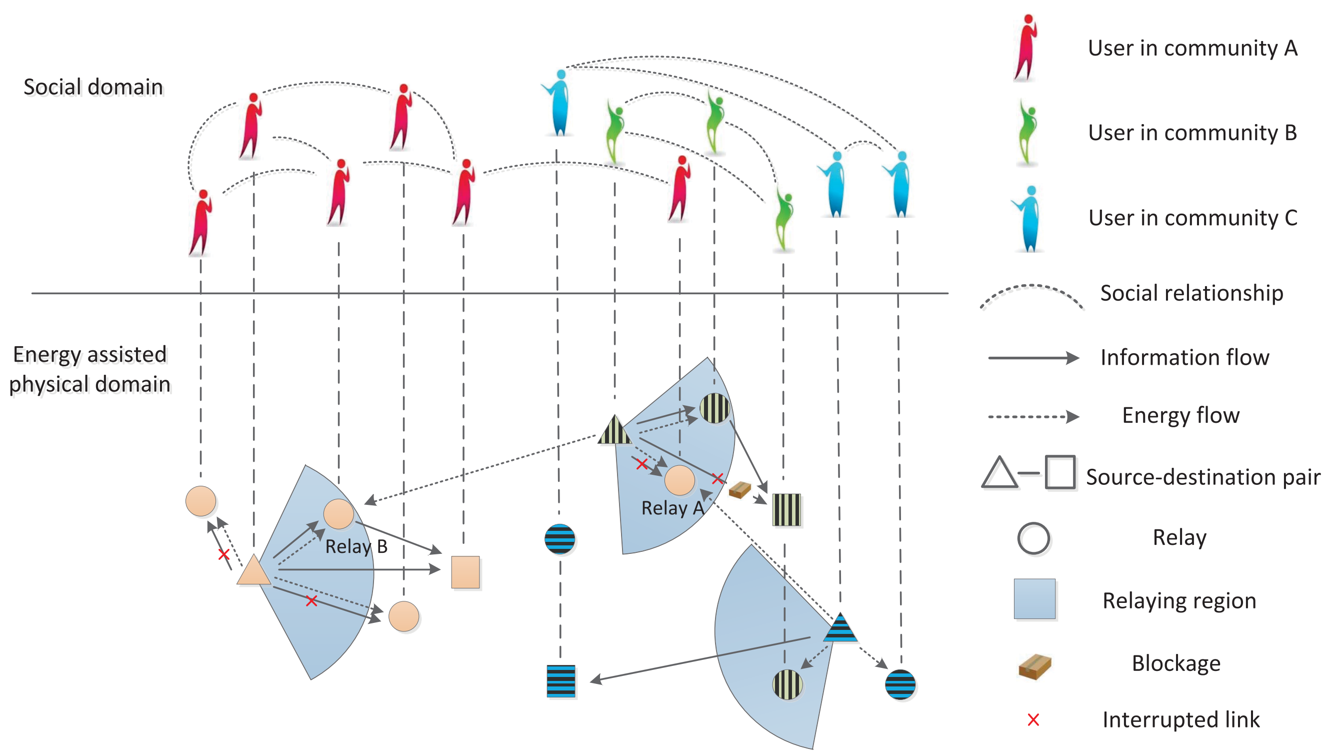

FIGURE 1. **Social-aware Energy Harvesting M2M Architecture.**

modeled by a real mobility measurement, which is conducted by Sassy for seventy-nine days [22]. The recorded encounters of every involved member are utilized to deduce contact frequency, illustrating the social-ties between the source and the relay. For example, if the two nodes contact each other frequently, there exists a strong social-tie between them. In this case, we define the relay attaining strong social-ties with the sources belonging to one community as the conversant relay of this community, as shown by the relay and the source with the same pattern in Fig. 1.

In the energy assisted physical domain, we consider a large-scale M2M network on $\mathbb{R}^2$, which contains K co-existing communities. Each community consists of multiple source-destination pairs. The sources in the k^{th} community[1] are distributed according to a HPPP Θ_k with density λ_k and the associated destination of each source is located at a distance of d_k away in a random direction. Since it is difficult for the transmitted signal to reach the destination due to severe blockage or path loss, communication can be conducted via cooperative relays. Therefore, there is a group of decode-forward (DF) relays distributed according to a HPPP Θ_r with density λ_r. Moreover, it is assumed that the sources are continuously connected to a power supply and the transmission power is P_k. The relays have no direct power supply and harvest energy from both the useful RF signal transmitted by the corresponding source and the detrimental interference transmitted by other sources. The relays have no traffic and only the conversant relay is dedicated to assisting the data transfer of conversant sources with the harvested energy. For instance, if a conversant relay of community A is adjacent to the source belonging to community B, it is reluctant to cooperate data transmission due to the weak social-ties (see relay A in Fig. 1). Furthermore, only the conversant relay that can decode the signal from the sources and is located in a relaying region is selected as the relay for the source (see relay B in Fig. 1). This can be classified into three constraints i.e., social networking constraint, physical proximity constraint and the DF constraint. In addition, it is assumed that the relays receive and forward signals over two different frequency bands.

The propagation channel is modeled as the combination of small-scale Rayleigh fading and large-scale path loss given by

$$g(r) = h_k \sqrt{r(x_1, x_2)^{-\alpha}}, \tag{1}$$

where h_k denotes the channel coefficient and the channel power gain $|h_k|^2$ follows exponential distribution with unit mean. $r(X, Y)$ represents the propagation distance between X and Y and $\alpha > 2$ is the path loss exponent.

B. TRANSMISSION MODE

We consider an energy harvesting and social-aware relay assisted cooperative transmission protocol, and restrict the number of hops between any source-destination pair to be two. The transmission is performed in two orthogonal time slots with two steps:

1) BROADCASTING PHASE

In the first step, all the sources simultaneously broadcast their signals with transmission power P_k. The relays utilize part of the received RF signals for energy harvesting and the remaining part for information decoding with a power splitting ratio ρ $(0 < \rho < 1)$.

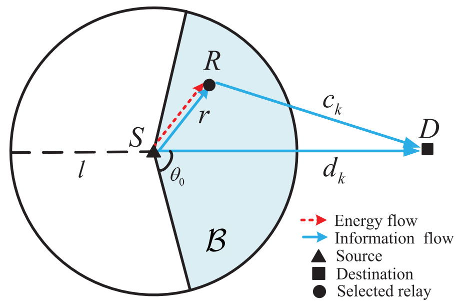

FIGURE 2. System model.

As mentioned above, the relay link is subject to the physical proximity constraint, the social networking constraint and the DF constraint. Firstly, the physical proximity constraint is defined for each source. In Fig. 2, a reasonable choice of such a physical proximity zone is a sector defined by a maximum angle θ_0 and a maximum distance l [23], which is denoted as $\mathcal{B} = \{r \in [0, l], \theta \in [-\theta_0, \theta_0]\}$. Secondly, a social graph $\Im \triangleq \{\Lambda, \xi\}$ is utilized to model the social networking constraint, where Λ is the vertex set that contains all the nodes in the whole network and ξ is the edge set given by

$$\xi = \left\{(i, j) : \varphi_{ij} \geq \varphi_{th}, \forall i, j \in \Lambda\right\}, \tag{2}$$

where φ_{ij} denotes the strength of the social-tie between node i and j, and φ_{th} is the threshold of the social strength. $\varphi_{ij} \geq \varphi_{th}$ represents the strong social-tie between node i and j. Therefore, the set of conversant relays that have strong social-ties with the source i can be given by $\Theta_{cr} = \left\{j \in \Lambda : \varphi_{ij} \geq \varphi_{th}\right\}$. If any of these relays belonging to Θ_{cr} successfully decodes the source's message and is located in the physical proximity zone, it becomes a member of the potential relays of the corresponding source.

2) RELAYING PHASE

In the second step, we propose two relay selection strategies named SRRS and SBRS to select one of the potential relays and utilize the selected relay to assist the transmission from the source to the destination.

In SRRS, we randomly select the relay from the set of potential relays. While SBRS selects the relay with the best

[1] It is assumed that there are K communities in the network. Without loss of generality, we will analyze the performance of the k^{th} community.

signal strength as follows.

$$\mathbb{R}=\arg\max_{x_r\in\Theta_{rp}}\left\{|h_{rD}^k|^2 r\left(x_r,x_D^k\right)^{-\alpha}\right\},\tag{3}$$

where Θ_{rp} denotes the set of potential relays for the source-destination pair in the k^{th} community and $|h_{rD}^k|^2$ is the channel power gain between the relay x_r and the destination x_D^k.

C. PERFORMANCE METRIC

In this paper, two representative performance metrics including outage probability and network throughput are characterized [3], which are defined as follows.

1) OUTAGE PROBABILITY

Outage probability is the probability that a destination node decodes the received data packets unsuccessfully from its corresponding transmitter. Specifically, given the signal-to-interference-plus-noise ratio (SINR) and a corresponding SINR target represented by Ω, the outage probability can be calculated by

$$p_{out}=Pr(SINR<\Omega).\tag{4}$$

2) NETWORK THROUGHPUT

Network throughput is the maximum rate the system can achieve under successful transmission with unit bits/sec. By assuming that the source transmission rate target is $\log(1+\Omega)$, the network throughput is given by

$$C=(1-p_{out})\cdot\log(1+\Omega).\tag{5}$$

III. PERFORMANCE ANALYSIS OF ENERGY HARVESTING AND SOCIAL-AWARE COOPERATIVE TRANSMISSION

In this section, we firstly derive the outage probability of energy harvesting and the social-aware cooperative transmission protocols and then characterize the network throughput. As shown in Fig. 2, we consider a typical source S in the k^{th} community network at the origin and its associated receiver D at the location $[d_k,0]$. R represents the selected relay. Without loss of generality, the performance of this typical communication transmission applies for any node according to Slivnyak's Theorem [24, 8.5].

A. DIRECT TRANSMISSION

We firstly consider the direct transmission without any relay, and thus the data transmission is conducted in a single time slot. All the sources simultaneously transmit information to their associated receivers. Consequently, the SINR at a typical receiver in the k^{th} community x_D^k can be written as

$$SINR_{DL}^k=\frac{P_k|h_0^k|^2{d_k}^{-\alpha}}{P_kI_k+\sum\limits_{\substack{j=1\\j\neq k}}^{K}P_jI_j+\sigma^2},\tag{6}$$

where $|h_0^k|^2$ is the channel power gain for the link from the source x_s^k to the destination x_D^k. $I_k=\sum_{x_s^k\in\Theta_k}|h_{x_s^k,x_D^k}|^2 r\left(x_s^k,x_D^k\right)^{-\alpha}$ and $I_j=\sum_{x_s^j\in\Theta_j}|h_{x_s^j,x_D^k}|^2 r\left(x_s^j,x_D^k\right)^{-\alpha}$ denote the interference from the k^{th} community and other communities at the destination x_D^k, respectively. $|h_{m,n}|^2$ denotes the power gain of channel between the nodes m and n. σ^2 represents the power of the additive white Gaussian noise (AWGN). According to (4), we have the following result.

Result 1: The outage probability for the direct transmission is given by

$$\Xi_{DL}^k=1-\exp\left(-\frac{\sigma^2\Omega{d_k}^{\alpha}}{P_k}\right)\exp\left(-\lambda_k\kappa d_k^2\Omega^{\frac{2}{\alpha}}\right)\times\exp\left(-\sum_{j=1,j\neq k}^{K}\lambda_j\kappa{d_k}^2\left(\frac{P_j\Omega}{P_k}\right)^{\frac{2}{\alpha}}\right),\tag{7}$$

where $\kappa=\pi\Gamma\left(1+\frac{2}{\alpha}\right)\Gamma\left(1-\frac{2}{\alpha}\right)$.

Proof: For the direct transmission, the outage probability can be calculated as

$$\begin{aligned}\Xi_{DL}^k&=\Pr\left\{SINR_{DL}^k<\Omega\right\}\\&=\Pr\left\{\frac{P_k|h_0^k|^2{d_k}^{-\alpha}}{P_kI_k+\sum\limits_{j=1,j\neq k}^{K}P_jI_j+\sigma^2}<\Omega\right\}\\&=\Pr\left\{|h_0^k|^2<I_kd_k^\alpha\Omega+\frac{\sum\limits_{j=1,j\neq k}^{K}P_jI_jd_k^\alpha\Omega}{P_k}+\frac{\sigma^2d_k^\alpha\Omega}{P_k}\right\}\\&=1-\exp\left(-\frac{\sigma^2d_k^\alpha\Omega}{P_k}\right)\mathbb{E}_{I_k}\left[\exp\left(-I_kd_k^\alpha\Omega\right)\right]\\&\quad\times\mathbb{E}_{I_j}\left[\prod_{j=1,j\neq k}^{K}\exp\left(-\frac{P_jI_jd_k^\alpha\Omega}{P_k}\right)\right].\end{aligned}\tag{8}$$

It is noted that $\mathbb{E}_{I_k}\left[\exp\left(-I_kd_k^\alpha\Omega\right)\right]$ is the Laplace transform of the random variable I_k with the input parameter Ωd_k^α. According to the Theorem in [24, 5.1], the Laplace transform of a HPPP Φ modeled process with density $\lambda>0$, denoted by $I=\sum_{T\in\Phi}|h_T|^2|T|^{-\alpha}$ with the input parameter s is given by

$$L_I(s)=\exp\left(-s^{\frac{2}{\alpha}}\lambda\kappa\right),\tag{9}$$

where $\left\{|h_T|^2\right\}$ is the independent identically distributed exponential random variables with unit mean. On this base, the Laplace transforms of the random variables I_k and I_j in (8) are calculated as

$$L_{I_k}\left(\Omega d_k^\alpha\right)=\exp\left(-\left(\Omega d_k^\alpha\right)^{\frac{2}{\alpha}}\lambda_k\kappa\right),\tag{10}$$

$$L_{I_j}\left(\frac{P_jd_k^\alpha\Omega}{P_k}\right)=\exp\left(-\left(\frac{P_j}{P_k}\right)^{\frac{2}{\alpha}}\Omega^{\frac{2}{\alpha}}d_k^2\lambda_j\kappa\right).\tag{11}$$

Then, the outage probability of the direct transmission can be obtained by substituting (10) and (11) into (8). This completes the proof of Result 1. □

B. COOPERATIVE TRANSMISSION WITH SRRS

For the relay assisted transmission mode, the transmission is conducted in two steps. In the first step, the relay splits the power of received signals from all the sources into two parts with a power splitting ratio ρ. The SINR at the relay x_r and the energy harvested by the relay are given by

$$SINR_1^k = \frac{(1-\rho) P_k |h_1^k|^2 r^{-\alpha}}{(1-\rho)\left(P_k I_k' + \sum\limits_{j=1, j\neq k}^{K} P_j I_j'\right) + \sigma^2}, \tag{12}$$

$$P_r^k = \eta \cdot \left[\rho P_k \left(|h_1^k|^2 r^{-\alpha} + I_k'\right) + \sum_{j=1, j\neq k}^{K} P_j I_j'\right], \tag{13}$$

where r is the distance between the typical source and the relay and $|h_1^k|^2$ is the channel power gain for the corresponding link. $I_k' = \sum\limits_{x_s^k \in \Theta_k} |h_{x_s^k, x_r}|^2 r\left(x_s^k, x_r\right)^{-\alpha}$ and $I_j' = \sum\limits_{x_s^j \in \Theta_j} |h_{x_s^j, x_r}|^2 r\left(x_s^j, x_r\right)^{-\alpha}$ represent the interference which comes from the k^{th} community and other communities at the relay node x_r. η $(0 < \eta \leq 1)$ denotes the energy harvesting efficiency.

Note that the potential relays for the corresponding source are limited by three constraints, i.e., the DF constraint, the social networking constraint and the physical proximity constraint. For the first two constraints, we define Θ_{sp} as the set of the conversant relays which can successfully decode the signal transmitted by the source. On one hand, social networking constraint defines the conversant relay as an individual who has strong social-ties with the corresponding source and is willing to assist the transmission of the conversant sources. The probability of the conversant relays can be obtained by the statistical results of the measurement and is defined as

$$p_{so} = \Pr\left\{\varphi_{ij} \geq \varphi_{th}\right\}, \tag{14}$$

On the other hand, the relay can successfully decode the transmitted signal with the probability defined as

$$\begin{aligned} p_{sec} &= \Pr\{SINR_1^k \geq \Omega\} \\ &= \mathbb{E}_r\left[\exp\left(-\frac{\sigma^2 \Omega r^{\alpha}}{(1-\rho) P_k}\right) \exp\left(-\lambda_k \kappa r^2 \Omega^{\frac{2}{\alpha}}\right)\right. \\ &\quad \left. \times \exp\left(-\sum_{j=1, j\neq k}^{K} \lambda_j \kappa r^2 \left(\frac{P_j \Omega}{P_k}\right)^{\frac{2}{\alpha}}\right)\right], \end{aligned} \tag{15}$$

and thus the density of the set Θ_{sp} is $\lambda_t \cdot p_{sec} \cdot p_{so}$.

For the physical proximity constraint, the probability that a relay belonging to Θ_{sp} is not included in the relaying region $\mathcal{B}$ can be calculated by using fundamental properties of a HPPP process $\Pr\{N(\mathcal{B}) = 0\} = \exp\left(-\int_{\mathcal{B}} \lambda(x)\, \mathbf{d}x\right)$ [24, 2.4.3], which is given by

$$\begin{aligned} \Xi_e^k &= \exp\left(-\int_{\mathcal{B}} \lambda_t \cdot p_{sec} \cdot p_{so} \mathbf{d}x\right) \\ &= \lambda_t \cdot p_{so} \cdot \exp\left(-\int_{-\theta_0}^{\theta_0} \int_0^{l} \exp\left(-\frac{\sigma^2 \Omega r^{\alpha}}{(1-\rho) P_k} - \lambda_k \kappa r^2 \Omega^{\frac{2}{\alpha}}\right)\right. \\ &\quad \left. \times \exp\left(-\sum_{j=1, j\neq k}^{K} \lambda_j \kappa r^2 \left(\frac{P_j \Omega}{P_k}\right)^{\frac{2}{\alpha}}\right) r \mathbf{d} r \mathbf{d}\theta\right). \end{aligned} \tag{16}$$

Note that only one of the potential relays under these three constraints is selected. Therefore, all the selected relays in the entire network form another HPPP Θ_{rp} with density $\sum\limits_{k=1}^{K}(1-\Xi_e^k)\lambda_k$.

In the second step, the relay x_r selected by SRRS retransmits the information to the associated receiver with transmission power P_r^k given in (13). In this case, the SINR at the typical receiver x_D^k is written as

$$SINR_2^k = \frac{P_r^k |h_2^k|^2 c_k^{-\alpha}}{P_r^k I_r + \sigma^2}, \tag{17}$$

where $|h_2^k|^2$ is the channel power gain for the link from the relay to the destination and $c_k = \sqrt{d_k^2 + r^2 - 2 d_k r \cos\theta}$ is the distance between x_r and x_D^k. $I_r = \sum\limits_{x_r \in \Theta_{rp}} |h_{x_r, x_d^k}|^2 r\left(x_r, x_D^k\right)^{-\alpha}$ denotes the total interference at the destination x_D^k.

Correspondingly, the outage probability of the second step is derived as

$$\begin{aligned} \Xi_r^k &= \Pr\{SINR_2^k < \Omega\} = \Pr\left\{\frac{P_r^k |h_2^k|^2 c_k^{-\alpha}}{P_r^k I_r + \sigma^2} < \Omega\right\} \\ &= 1 - \int_{-\theta_o}^{\theta_o} \int_0^{d_2} \exp\left(-\frac{\sigma^2 \Omega c_k^{\alpha}}{P_r^k}\right) \\ &\times \exp\left(-\sum_{k=1}^{K} (1-\Xi_e^k) \lambda_k \kappa \Omega^{\frac{2}{\alpha}} \left(d_k^2 + r^2 - 2 d_k r \cos\theta\right)\right) r dr d\theta \end{aligned} \tag{18}$$

The direct transmission and the relaying transmission are combined with a selective combining (SC) method [25] at the destination. This forms the cooperative transmission, which indicates that the information decoding is based on an opportunistic mode. It is well known that SC only requires relative SINR measurements and doesn't need the channel state information. Thus, it suffers from a lower complexity compared with other diversity techniques. With SC diversity at the destination node, outage occurs if neither the direct transmission nor the relaying transmission can support the target SINR. Hence, we have the following results.

1) THE OUTAGE PROBABILITY OF RELAYING TRANSMISSION WITH SRRS

In the absence of direct link, the outage occurs if there is no potential relay for the source or the second step of the relaying link is interrupted. Therefore, in the k^{th} community network, the outage probability of relaying transmission with SRRS is given by

$$\Xi^k_{r_{SRRS}} = \Xi^k_e + (1 - \Xi^k_e) \cdot \Xi^k_r. \tag{19}$$

2) THE OUTAGE PROBABILITY OF COOPERATIVE TRANSMISSION WITH SRRS

For the cooperative transmission, the outage of SRRS occurs if neither the direct link nor the relaying transmission can support the target SINR. Then, in the k^{th} community network, the outage probability of cooperative transmission with SRRS is given by

$$\Xi^k_{c_{SRRS}} = \Xi^k_{DL} \cdot \Xi^k_e + \Xi^k_{DL} \cdot (1 - \Xi^k_e) \cdot \Xi^k_r. \tag{20}$$

3) THE NETWORK THROUGHPUT WITH SRRS

The network throughput is defined as the total amount of data that is successfully received by the destinations, which can be evaluated by the expressions in (5). Then, the network throughput with SRRS is given as follows.

$$C_{SRRS} = \sum_{k=1}^{K} \lambda_k \left(1 - \Xi^k_{c_{SRRS}}\right) \log\left(1 + \Omega\right). \tag{21}$$

C. COOPERATIVE LINK WITH BEST RELAY SELECTION

In this case, the relaying transmission in the first step is the same as Section III-B. For the second step, SBRS employs the relay which achieves the best power gain of the forwarding channel. Correspondingly, the outage probability of the second step is derived as follows.

$$\Xi^k_{r'} = exp\left(-\int_{-\theta_0}^{\theta_0}\int_0^l \left(\exp\left(-\sum_{k=1}^{K}(1-\Xi^k_e)\lambda_k\kappa c_k^2 \Omega^{\frac{2}{\alpha}}\right) \times \exp\left(-\frac{\Omega\sigma^2 c_k^\alpha}{P_r^k}\right)\right) r\mathbf{d}r\mathbf{d}\theta\right) \tag{22}$$

Proof: For the SBRS, from (3), we have

$$\begin{aligned}
\Xi^k_{r'} &= 1 - \Pr\left(\max_{x_r\in\Theta_{bp}}\left\{\frac{P_r^k|h_2^k|^2 c_k^{-\alpha}}{P_r^k I_r + \sigma^2}\right\} \geq \Omega\right)\\
&= \mathbb{E}_{I_r}\left[\prod_{x_r\in\Theta_{bp}} 1_{\left\{\frac{P_r^k|h_2^k|^2 c_k^{-\alpha}}{P_r^k I_r+\sigma^2}<\Omega\right\}}\right]\\
&= \mathbb{E}_{I_r}\left[\prod_{x_r\in\Theta_{bp}}\left(1-\exp\left(-\Omega I_r c_{x_r}^\alpha\right)\exp\left(-\frac{\Omega\sigma^2 c_{x_r}^\alpha}{P_r^k}\right)\right)\right]\\
&\overset{(a)}{=} \mathbb{E}_{I_r}\left[\exp\left\{-\int_{\mathcal{B}}\left(1-\exp\left(-\Omega I_r c_k^\alpha\right) \times \exp\left(-\frac{\Omega\sigma^2 c_k^\alpha}{P_r^k}\right)dx\right\}\right]\\
&\overset{(b)}{=} \exp\left(-\int_{-\theta_0}^{\theta_0}\int_0^l\left(\exp\left(-\sum_{k=1}^{K}(1-\Xi^k_e)\lambda_k\kappa c_k^2\Omega^{\frac{2}{\alpha}}\right) \times \exp\left(-\frac{\Omega\sigma^2 c_k^\alpha}{P_r^k}\right)\right) r\mathbf{d}r\mathbf{d}\theta\right),
\end{aligned} \tag{23}$$

where Θ_{bp} denotes the non-empty set, (a) follows from the probability generating functional (PGFL) of the HPPP defined in [24], and (b) follows from the proof of Result 1. The proof is thus completed. □

On this base, we have the following results.

1) THE OUTAGE PROBABILITY OF RELAYING TRANSMISSION WITH SBRS

Without consideration of the direct link, the outage occurs if the set of potential relays is empty or the second step of the relaying link is interrupted. Then, the outage probability of relaying transmission with SBRS is given by

$$\Xi^k_{r_{SBRS}} = \Xi^k_e + (1 - \Xi^k_e) \cdot \Xi^k_{r'}. \tag{24}$$

2) THE OUTAGE PROBABILITY OF COOPERATIVE TRANSMISSION WITH SBRS

For the cooperative transmission, the outage occurs if neither the direct link nor the relaying transmission can support the target SINR. Then, the outage probability of cooperative transmission with SBRS is given by

$$\Xi^k_{c_{SBRS}} = \Xi^k_{DL} \cdot \Xi^k_e + \Xi^k_{DL} \cdot (1 - \Xi^k_e) \cdot \Xi^k_{r'}. \tag{25}$$

3) THE NETWORK THROUGHPUT WITH SBRS

The network throughput is defined as the total amount of data that is successfully received by the destinations, which can be evaluated by the expressions in (5). Then, the network throughput with SBRS is given as follows.

$$C_{SBRS} = \sum_{k=1}^{K} \lambda_k \left(1 - \Xi^k_{r_{SBRS}}\right) \log\left(1 + \Omega\right). \tag{26}$$

IV. NUMERICAL RESULTS

In this section, numerical results are provided to verify our theoretical analysis. Unless otherwise specified, the parameter settings in the simulation are listed in Table 1. Moreover, 10000 Monte-Carlo experiments are conducted for every point in each figure and "theo" represents the theoretical results.

Fig. 3 compares the outage probabilities versus transmission power P for the direct transmission, relaying and cooperative transmissions with different relaying strategies. The observations are given as follows. Firstly, it can be observed that the simulated outage probabilities are quite consistent with our analytical results for the different values of P, proving the correctness of our deductions. Secondly, there is a crossing point between the direct transmission and relaying

[2] It corresponds to a city cellular network environment.

TABLE 1. Parameter settings.

Parameter	Setting
The number of co-existing communities	$K = 2$
The distance between S and D	$d = d_1 = d_2 = 16$ meters (m)
The radius of the relaying area	$l = 8$ m
The density of the sources	$\lambda = \lambda_1 = \lambda_2 = 0.001/m^2$
The density of the relays	$\lambda_r = 0.001/m^2$
The angel	$\theta_0 = \arccos\left(\frac{l}{2d_1}\right)$
Source transmission power	$P = P_1 = P_2 = 20$ dBm
Time of transmission slot	$T = 1$ s
Path-loss exponent	$\alpha = 4^2$
The power splitting ratio	$\rho = 0.5$
Energy harvesting efficiency	$\eta = 1$
The SINR target	$\Omega = -10$ dB
The power of the AWGN	$\sigma^2 = -75$ dBm
The threshold of the social strength	$\varphi_{th} = 0.5.$

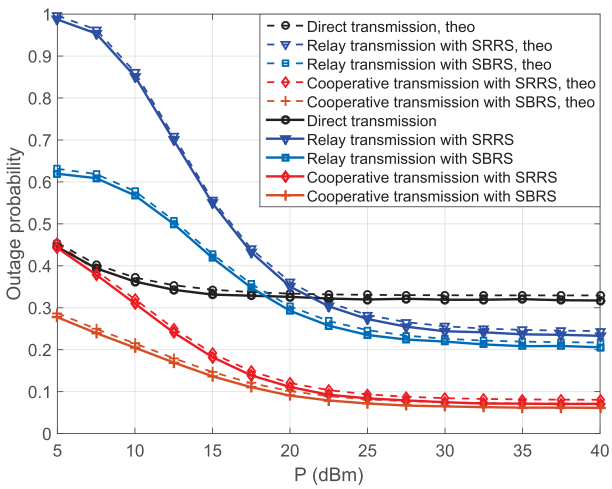

FIGURE 3. The outage probabilities versus the transmission power of the source for the direct transmission, relaying transmissions and cooperative transmissions.

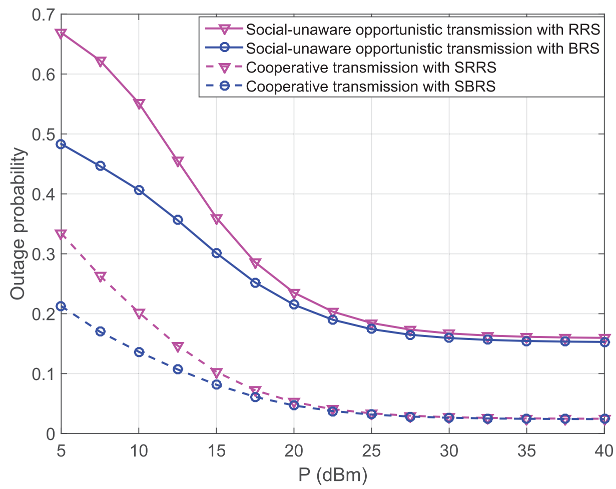

FIGURE 4. The outage probabilities versus the transmission power of the source for the cooperative transmission and social-unaware opportunistic transmission with different relaying strategies.

transmission. The direct transmission outperforms the relaying transmission when the transmitting power is small, while the opposite scenario occurs when P increases. This can be explained by the reason in twofold. On one hand, P influences the average number of relays and a larger P results in an extended range of physical proximity zone. On the other hand, the transmitting power of the relay increases with P. Thirdly, Fig. 3 shows that the cooperative transmission yields superior performance than direct and relaying transmissions, proving the gain of the cooperative diversity. Moreover, the transmission with SBRS strategy performs a lower outage probability than SRRS. This is because the best relaying link is selected for transmission in SBRS. In particular, for the SRRS strategy, the larger P increases the probability of randomly selecting a relay with good quality. Therefore, SRRS approaches to SBRS when P approaches to infinity.

Fig. 4 compares the outage probabilities for the social-aware cooperative transmissions and the social-unaware opportunistic transmissions versus the transmission power P. In social-unaware opportunistic transmission, the source transmits the signal to its associated destination via selecting the best link between the direct transmission and relaying transmission without considering the social networking constraint [26]. Moreover, we set the density of the source as $\lambda = 5 \times 10^{-4}$. In Fig. 4, the cooperative transmissions perform lower outage probabilities than social-unaware opportunistic transmission with different transmission power. Specifically, the cooperative transmission with the SBRS yields 82% improvement of outage probability over the social-unaware opportunistic transmission at $P = 25$. This can be explained by the fact that the relay selected without considering social awareness may be unwilling to assist the transmission with its harvested energy due to weak social-tie with the corresponding source. Moreover, Fig. 4 illustrates that all the curves converge to a constant as P becomes larger. This is because the network becomes interference-limited as P increases.

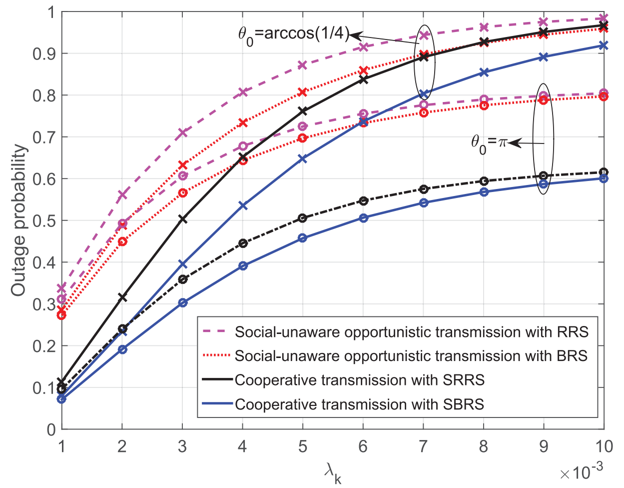

FIGURE 5. The outage probabilities versus the density of the sources for the cooperative transmission and social-unaware opportunistic transmission with different angles θ_0.

Fig. 5 plots the outage probabilities versus the density of the sources for the cooperative transmissions and social-unaware opportunistic transmissions with different angles θ_0. The curves in Fig. 5 show that a smaller angel ($\theta_0 = \arccos \frac{1}{4}$) can further protect the transmission from the assistance by a long-distance relay and thus achieves better performance than $\theta_0 = \pi$. Moreover, it can be observed that BRS achieves better performance in the outage probability than RRS with or without social factors. This further strengthens the analysis of these two relaying selection strategies.

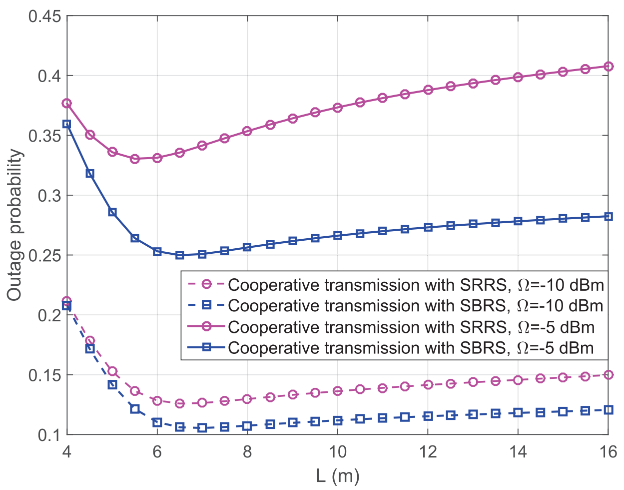

FIGURE 6. The outage probabilities versus the radius of the physical proximity zone for the cooperative transmissions with different SINR targets Ω.

In Fig. 6, we characterize the outage probabilities of the cooperative transmissions versus the radius of the physical proximity zone l. It is observed that the outage probability firstly decreases to a minimum value with l, but then starts to increases when l is above a certain value. This can be explained in two steps accordingly. Firstly, the probability of a non-empty set of the potential relay increases with l and thus the receiver has a higher probability to enjoy the cooperative diversity, resulting in a decrease in outage probability. Secondly, when l grows beyond a certain value, the probability of selecting a long-distance relay increases. The larger path loss results in the decreases of the harvested energy and the SINR at the relay node. Therefore, the outage probability increases with l. Furthermore, we can draw a conclusion that a smaller Ω reduces the outage probability according to (4) and Fig. 6 illustrates that SBRS outperforms SRRS from the perspective of the radius of the relaying zone and the SINR targets.

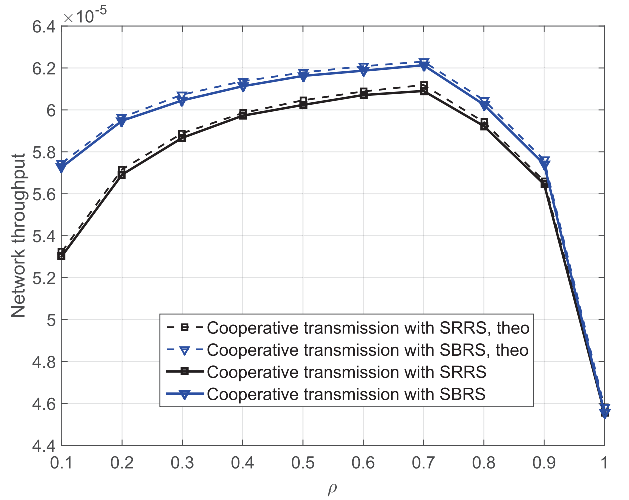

FIGURE 7. The network throughput versus the power splitting ratio for the cooperative transmissions.

In Fig. 7, we characterize the network throughput of the cooperative transmissions versus the power splitting ratio ρ. It can be observed that there is an optimal power spitting ratio ρ^* yielding the maximum network throughput. This can be explain by the fact that for the small value of ρ, there is less power available for energy harvesting. Therefore, the relaying transmission may be interrupted as the scarce energy harvested by the relay and the high outage probability results in low network throughput. When the value of ρ is larger than the optimal value, there is not enough power for information decoding and then smaller network throughput occurs due to the outage of the relaying transmission. Moreover, the simulation results are quite consistent with our theoretical analysis and thus our results can be utilized to seek the optimal power spitting ratio and guide the practical network deployment.

The network throughput for the cooperative transmissions with SRRS and SBRS is illustrated in Fig. 8. It can be observed that the cooperative transmission with SBRS achieves a higher network throughput than SRRS, which further validates our previous analysis. The network throughput

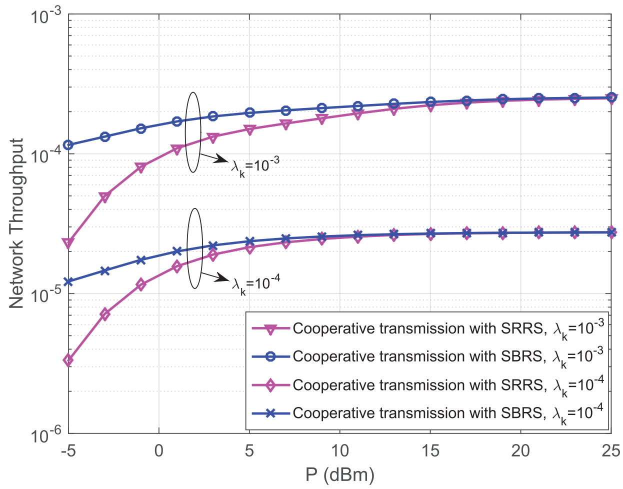

FIGURE 8. The network throughput versus the transmission power of the sources for the cooperative transmissions with different densities of the sources.

of these two methods converges to the same as the transmission power increases. This can be explained by the fact that the transmitting power of the relay increases with P. When P is above a certain value, the transmitting power of the relay selected by SRRS or SBRS approaches the same, resulting in the similar throughput. Moreover, the outage probability increases with the density of the source λ, which proves that the interference from multiple sources has a significant influence on the receivers.

V. CONCLUSION

In this paper, we propose a large-scale M2M network architecture with energy harvesting and social-aware relays, which consists of the energy assisted physical domain and the social domain. In the energy assisted physical domain, a large-scale network overlaid with multiple co-existing communities has been studied using a stochastic geometry model, where M2M transmitter-receiver pairs and relays form independent HPPPs. In the social domain, the relay is conversant with some communities and is willing to assist the data transfer of conversant sources. An energy harvesting and social-aware relay assisted cooperative transmission protocol is proposed with SRRS and SBRS. The performance of the proposed transmission protocols are numerically evaluated. Simulation results show that the proposed social-aware cooperative transmission protocol yields superior performance over existing protocols without considering social networking characteristics.

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