IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received March 31, 2016, accepted May 1, 2016, date of publication August 24, 2016, date of current version September 28, 2016.

Digital Object Identifier 10.1109/ACCESS.2016.2601031

Fountain Coded Cooperative Communications for LTE-A Connected Heterogeneous M2M Network

AHASANUN NESSA[1], (Student Member, IEEE), MICHEL KADOCH[1], (Senior Member, IEEE), AND BO RONG[2], (Member, IEEE)
[1]Department of Electrical Engineering, Ecole de Technologie Superieure, Universite du Quebec, Montreal, QC H3C 1K3, Canada
[2]Communications Research Center Canada, Ottawa, ON K2H 8S2, Canada

Corresponding author: A. Nessa (ahasanun.nessa.1@ens.etsmtl.ca)

ABSTRACT Machine-to-machine communication over long-term evolution advanced (LTE-A) network has emerged as a new communication paradigm to support a variety of applications of Internet of Things. One of the most effective techniques to accommodate a large volume of machine type communication (MTC) devices in LTE-A is clustering where devices (nodes) are grouped into number of clusters and forward their traffics to the base station (e.g., LTE eNodeB) through some special nodes called cluster heads (CHs). In many applications, the CHs change location with time that causes variation in distances between neighboring CHs. When these distances increase, the performance of data transmission may degrade. To address this issue, we propose to employ intermediate non-CH nodes as relays between neighboring CHs. Our solution covers many aspects from relay selection to cooperative formation to meet the user's QoS requirements. As the number of total relay plays a significant role in cooperative communications, we first design a rateless-coded-incremental-relay selection algorithm based on greedy techniques to guarantee the required data rate with a minimum cost. After that, we develop both source-feedback and non-source-feedback-based fountain coded cooperative communication protocols to facilitate the data transmission between two neighbor CHs. Numerical results are presented to demonstrate the performance of these protocols with different relay selection methods under Rayleigh fading channel. It shows that the proposed source-feedback-based protocol outperforms its non-source-feedbackprotocol counterpart in terms of a variety of metrics.

INDEX TERMS Internet of things, fountain codes, machine to machine communication, cooperative communications.

I. INTRODUCTION

Over the last couple of decades, future Internet design has attracted significant attention from both academia and industry. The future Internet is likely to integrate heterogeneous communication technologies, both wired and wireless, contributing substantially to assert the concept of Internet of Things (IoT) [1]. IoT is defined as a worldwide network of interconnected objects, where objects are equipped with tiny identifying devices, and intelligently transfers data over the network without any human intervention. Wireless sensor network plays an increasingly important role in the development of this emerging paradigm. It acts as an important data resource for IoT that collects the information from the surrounding environments, analyses the collected data and transmits to the Internet.

With the emergence of IoT, the conventional sensor nodes are being replaced by more technologically advanced nodes, namely machine nodes those have higher information processing features. This introduces a new paradigm in communication research, namely machine type communication (MTC) or machine to machine (M2M) communication [2]. Smart infrastructure, health care and electricity grids are a few possible applications [3]–[5] in which MTC may play a leading role to improve the quality of people's lives. M2M network can be considered as a generalization of traditional sensor network in terms of their higher processing capabilities and is very often installed in remote areas for sensing or surveillance purpose, where hundreds or thousands of machine type devices (nodes) are densely located over small or medium area [6].

In the past, tremendous technology development and commercial success have incurred in mobile cellular networks (MCNs). In cellular network paradigm, long-term evolution advanced (LTE-A) is the latest cellular communication standards, developed by the Third Generation Partnership Project (3GPP) to meet the requirements of International Mobile Telecommunications-Advanced (IMT-Advanced) systems [7], [8]. The ongoing massive deployment of LTE-A makes it possible to install M2M network in most urban and remote areas, and by using LTE-A backhaul networks, a seamless network communication is being established between MTC-nodes and -applications. It is expected, in the following years more than 2 billion of MTC devices will be interconnected in LTE-A network to support different applications in IoT paradigm [9]. Therefore, when a massive number of nodes will attempt to connect to an LTE-A base station (e.g. eNodeB), it is very likely that the network will be congested, and both MTC and non-MTC traffics will be affected. Many IoT applications, such as health care, industry automation and robot control demand stringent QoS requirements in terms of reliability, latency and scalability. Hence, it is crucial yet challenging to achieve reliability in M2M communications specially for time constrained applications.

Node clustering has been proven to be a promising solution in congestion control and reliable data transmission [10]–[12] in M2M communications. In this architecture, the nodes are grouped into a number of clusters and some nodes are chosen as CHs which are sometimes also referred as gateways [13]. The non CH nodes in each cluster send their data to their respective CHs and inter cluster traffics are forwarded through the CHs to the LTE-A base station (eNodeB). In many deployment scenarios, some machines are allowed to move and change their location in the deployment area with very low mobility, such as surveillance applications, animals in habitat monitoring applications, and traffic monitoring applications [14], [15]. As a consequence, when the neighboring CHs move apart from each other because of the mobility of the nodes, the performance of the data transmission may deteriorate below the threshold level. Therefore, CH needs to be reselected in such cases. However, frequent re-selection of CHs results in counter effect on routing and reconfiguration of resource allocation associated with CH-dependent protocols.

We identify this problem as a physical layer problem and as a solution we propose to employ cooperative communications between neighboring clusters. Cooperative communication is an effective way of improving the throughput, power efficiency and coverage in wireless networks [16]–[19]. Currently, the researchers are giving more emphasis to explore cooperative strategies and protocols to achieve higher performance and reliability in communications [16], [20]–[23]. In [24], [25], the authors analyzed cooperative communication based on distributed space-time block coding (STBC) for wireless sensor network and showed that cooperative communication is more energy efficient than non-cooperative direct communication. However, distributed STBC requires strict synchronization among transmitters, which is difficult and even impossible in most mobile cases. Previous works [24], [25] addressed the fixed rate code. The outage probability in their works cannot reach zero if the precise channel state information (CSI) is unavailable at the transmitter.

Among many other channel coding techniques, fountain code - a channel coding technique [26]–[28] that adapts its rate according to the variation of channel condition, has attracted a lot of research interest. For its capacity approaching potentiality and rateless property, it appears as a promising solution for data communication in many wireless communication systems including relay networks [19], [29] and cognitive radio systems [30]. As a promising feature, it does not require any synchronization mechanism like virtual multiple-input-multiple-output (MIMO). Also it does not require CSI at the transmitter as fixed rate code. In open literature, the work related to cooperative communications [20]–[25], [29] mainly focuses on the performance analysis and theoretical bound for certain specific models. There has been little research done on a full and practical solution for heterogeneous M2M networks.

In this work, we develop a set of schemes to support cooperative communication in LTE-A connected heterogeneous M2M networks. We investigate clustered heterogeneous M2M networks, and propose both source-feedback and non-source-feedback based cooperative communication protocols using fountain coding. We assume that the network consists of two or more types of nodes with respect to battery supply and functionality. The network is then further partitioned into a number of clusters, where more powerful nodes have been chosen as CHs. CHs emulate the role of the base stations in their respective clusters, and inter cluster traffics are forwarded through the CHs to the LTE-A network. Then LTE-A network relays the messages to servers and end users located in the application domain as shown in Fig. 1. Our schemes suggest that intermediate non-CH nodes between two neighboring CHs act as relays by forwarding the received information from the source CH to the destination CH. In our previous work [32], cooperative communication protocols using LT [26] code have been analyzed for different position of relay nodes over Rayleigh fading channel. In this work we propose source-feedback and non-source-feedback protocols using Raptor code [27] and compare the performance of theses protocols under different relay selection methods. In the source-feedback protocol, the source CH and relays transmit to the destination until the destination is capable to decode the source CH's information correctly. After successfully decoding the source CH's information, the destination CH sends acknowledgement (ACK) to source and relays. In the non-source-feedback protocol, source CH transmits to relay and the destination and then ceases its transmission after receiving ACKs of successful reception from relays hoping that destination can successfully receive the remaining information from relays. In both aforementioned protocols, all the nodes use their own fountain coding routine and different orthogonal channels to encode and transmit their data simultaneously. We study their performance in Rayleigh fading channel and show that by employing cooperative protocols

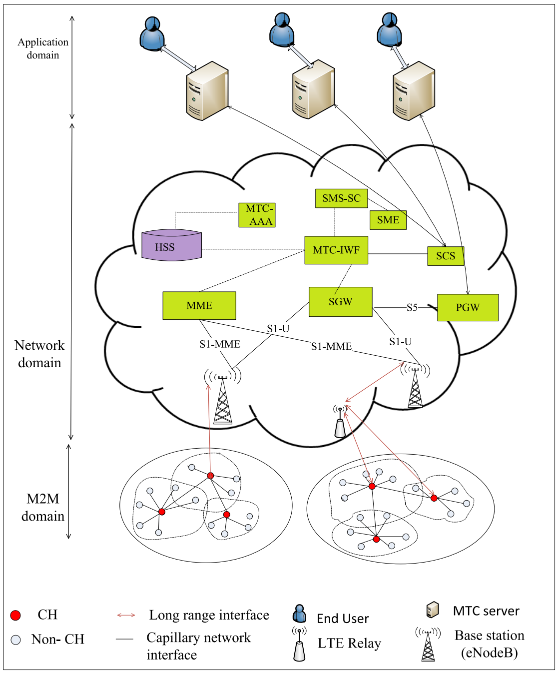


FIGURE 1. An LTE-A connected heterogeneous M2M networking architecture.

the performance of data transmission can be dramatically improved than the direct communication between two neighboring CHs.

Evidently the performance is improved as more relay nodes get involved. However, employing more relays between the source and the destination pair causes more signaling overhead and higher power consumption. In this regard, we focus on relay selections between two neighboring CHs aiming at achieving the target data rate between two clusters with the involvement of minimum number of relay nodes. The target data rate between two clusters, which is associated with the required end to end signal quality depending on the type of applications, is provided by the network designer. When a large number of non-CH nodes are available to be a relay, finding the optimum set by using conventional Brute-Force Search (BFS) would require huge computational effort that limits its application in practical systems. In order to reduce the computational complexity of searching the optimum set, we propose rateless coded incremental relay selection (RCIRS) algorithm based on greedy technique. In our approach, source CH collects the channel state information of neighboring nodes and includes some non-CH nodes in the cooperative group one by one so that the cooperative data rate is incrementally increased until it meets the target data rate. The relay selection proposed here is mainly for source-feedback protocol. However, it could easily be extended to the scenario of non-source-feedback protocol.

The main contributions of this paper are the following.

1) We identify the CH-to-CH channel as a bottleneck in heterogeneous M2M network, and present a full solution to support fountain coded cooperative communications. The proposed solution consists of several schemes from relay selection to cooperative strategy, while taking into account user's QoS requirements.
2) In most of the existing works, the number of cooperating nodes is either fixed [22] or random [21], [23], [24] depending on the channel and noise realizations. This work selects the cooperative nodes according to the data rate requirement. The proposed RCIRS algorithm takes into account the link between source CH to relay candidate and destination CH to relay candidate. Then it judiciously selects a minimum number of nodes while achieving the required data rate with much less computational complexity than BFS.
3) In this work, we also develop two communication protocols based on fountain coding, namely source-feedback and non-source-feedback cooperative communication protocols to improve the performance of data transmission between two neighboring CHs. We evaluate the performance of our proposed protocols with different relay selection method using the metric of transmission efficiency rather than the outage probability. This strategy is more realistic since in rateless coded systems, the outage probability is always driven to zero if there is no restriction on decoding delay.

The rest of the paper is organized as follows. We first review the existing work in Section II and introduce our system model of cooperative communications over clustered M2M networks in Section III. We then present the relay selection algorithm and fountain coded cooperative communication protocols in Section IV and Section V, respectively. Finally, Section VI demonstrates the simulation results and Section VII concludes our paper.

II. RELATED WORKS

In open literature, there exists several works investigating the performance of rateless codes over wireless relay channel. Castura and Yongyi [29] introduced the first rateless coding framework over relay channels, where the relay assists the source as a secondary antenna once it decodes source information successfully. In this framework, the relay node synchronizes itself with the source before starting transmission. The source and relay then transmit data to the destination using space time Alamouti code. Xi and Teng Joon [31] studied several single relay cooperative schemes and derived their achievable rate in flat Rayleigh fading channel. Yang and Host-Madsen [33] studied the performance of fountain codes in low power regimes. Abouei et al. [34] study the performance of fountain codes in wireless body area network with respect to reliability and energy consumption. In [17] Zhang et al. proposed a joint network-channel coding (JNCC) with Raptor code for a 2-1-1 system. They optimized the degree distribution of the Raptor code and showed that their proposed JNCC with optimized degree distribution outperforms conventional JNCC schemes in terms of BER and throughput performance. In [35], Nikjah et al. proposed several single parameter relay selection protocols based on information accumulation and rateless coding schemes. There, relay nodes send acknowledgement to the destination after successfully decoding the source information, and the destination then finds out the best relay to transmit information to the destination. In [36], Molisch et al. studied the performance of fountain code in the presence of multiple relay nodes under block fading Rayleigh channel, and showed that information accumulation consumes less energy and requires less transmission time than that of energy accumulation.

In cooperative communications, a relay node is located between the source and the destination and assists the communication in a two hop manner to achieve higher data rate than the data rate of direct link. In the literature, comprehensive studies have been given on relay selection in the cooperative communications with fixed code rate [37]–[40]. In [37], Zhao et al. showed for a single source-destination pair, the selection of the best relay node among multiple relay nodes can offer same level of performance as employing many ordinary relay nodes. In [38], Bletsas et al. proposed a distributed scheme for the selection of the single relay node in the presence of multiple relays based on instantaneous channel condition. In [39], the authors proposed threshold-based selective relaying schemes in order to minimize the end-to end bit error rate (BER) in cooperative decode and forward system. In [40], Bali et al. proposed a distributed scheme for multiple relay selection based on source and relay channel and threshold optimization. They assumed that all the relays have same average SNRs to the source and optimized the threshold value on this assumption. However, in practical, the relay nodes are located randomly between the source and the destination and experienced SNRs at relay nodes may vary according to the distance and fading of the wireless channel.

Most existing works on fixed code rate system address energy combination of orthogonal transmissions from different paths at the receiver. In rateless coded system, however, receiver collects mutual information from different independent paths to decode information. Therefore, the relay selection scheme for fixed rate code cannot provide the optimal throughput when applied to rateless coded cooperation. In fact, the investigation on the relay selection has not received much attention yet regarding the cooperative communications using rateless code. In [36], as soon as relay nodes decode the message, they start transmitting to the destination with the possibility of having a poor link. The existing works in [35], [38], and [41] mainly focus on how to select the best relay in the presence of multiple relay for a single source-destination pair so that the highest transmission rate can be achieved [35], [41]. In [35], the destination selects the best relay from a set of nodes after decoding the source information. The achievable data rate with the cooperation of a single relay may not be able to attain the target level. Moreover, in wireless M2M network, single relay selection may not be robust enough to provide reliability due to the link instability and resource limitation of the MTC nodes. Multiple relay selection utilizing the advantage of fountain codes becomes a critical challenge in such a research context, that we solve in our work.

III. SYSTEM MODEL

In this paper, we consider a clustered heterogeneous M2M network setting where the MTC nodes are grouped into a number of overlapping and disjoint clusters and some powerful nodes among them are selected as cluster heads (CHs) as illustrated in Fig. 1. In our setup, each cluster has a cluster head which coordinates transmissions within the cluster, collects data, communicates with neighboring clusters and forwards data to the LTE-A network. We also assume that nodes are equipped with both a long range and a short range interface. Nodes use short range radio interface to create an ad-hoc capillary network among the nodes in local M2M domain and long range interface to connect to LTE-A network. The reason behind clustering is to avoid congestion and increase the efficiency of data transmission by allowing limited number of nodes to access LTE-A network directly. Evidently the level of congestion control depends on the number of CHs. On the other hand, accommodating a large number of nodes in a cluster may also cause congestion inside a cluster. In the literature, comprehensive studies have been given on cluster design. Communication capability, communication link quality, storage status and battery status of each node are mainly considered during CH selection [10]–[12]. However, cluster design and CH selection are out of the scope of this paper. In this paper, we only focus on designing cooperative strategies with relay selection between two neighboring clusters.

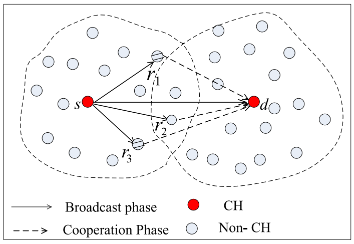


FIGURE 2. Cooperative communications framework over clustered M2M network.

Let's assume, the CH in a source cluster wants to send a message to the CH of a neighboring cluster. Unlike the conventional direct communications between CHs, we employ cooperative communications to improve the reliability of data transmission between two neighboring CHs. In Fig. 2, we show an example system model that consists of two overlapping clusters with many edge nodes that can sense signals from both CHs. This figure illustrates a simple scenario of data transmission between two overlapping clusters where source CH, s transmits data targeting destination CH, d. Exploiting the intrinsic nature of wireless medium, the neighbor nodes r_1, r_2, r_3 overhear the transmission between two CHs and are able to facilitate the transmission by forwarding the received information to the neighboring CHs.

TABLE 1. **Notation.**

Symbol	Definition
H	Number of bits in $relay\_probe$ message
C_{target}	Target end to end data rate of s-d pair
C_{sd}	Achievable data rate for s-d pair
C_{sr_i}	Achievable data rate for s-r_i pair
C_{r_id}	Achievable data rate for of r_i-d pair
C_{cdr}	Achievable cooperative data rate of the network
γ_{ab}	Channel gain of a-b pair
τ_{ab}	Time taken by b to decode $relay\_probe$ message transmitted by a
P_0	Transmission power of each node
$\mathcal{C}$	Set of initial relay candidates
$\mathcal{A}_x$	Set of successful relay candidates
$\mathcal{A}_{min}$	Set of selected relay nodes
N	Number of initial candidates in set $\mathcal{C}$
R	Number of relays in set $\mathcal{A}_{min}$
ζ	The transmission efficiency
$\Omega(x)$	Degree distribution of Raptor code in noisy channels
Z_{c_o}	Channel log likelihood ratio
$G_{a,b}$	Path loss between node a and node b

Correspondingly, r_1, r_2, r_3 act as relays between s and d, and thus d achieves diversity by receiving signals from different fading paths.

We assume, the transmit power of each transmit node s is restricted to P_s and the noise at each receive node j is assumed to be white gaussian with a variance of σ_j^2. Denoting the transmitted symbols of s as X, the received symbols at r_i and d can be expressed as

$$Y_j = H_{sj}X + W_j, \tag{1}$$

where $j = \{r_i, d\}$; W_j is the gaussian noise at j with variance σ_j^2; H_{sj} is modeled as $\sqrt{G_{sj}}h_{sj}$ where $h_{sj} \sim \mathcal{CN}(0, 1)$ which is a circularly symmetric complex Gaussian random variable with zero mean and unit variance, and G_{sj} denotes the path loss between node s and node j. Then the received SNR at j for a pair s-j can be expressed as

$$\gamma_{sj} = H_{sj}^2 P_s/\sigma_j^2. \tag{2}$$

In order to avoid interference, we assume that orthogonal channels [42], [43] are allocated to different terminals i.e., inter-user orthogonality. The source transmits to the destination and relays through one channel and the relays transmit to the destination through other different orthogonal channels. This assumption can be easily implemented in practice using orthogonal frequency division multiplexing (OFDM) modulated WiFi technology, where different sub-carriers are assigned to different users. After relay selection, we assume that all the nodes use their own fountain coding routine to encode the data. Table 1 lists the notation used in this paper. In the subsequent sections, we will use source node (destination node) and source CH (destination CH), interchangeably.

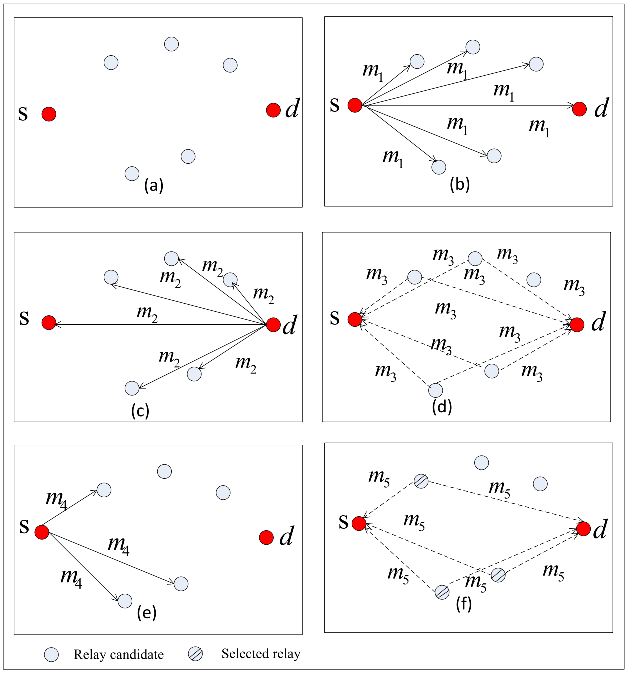


FIGURE 3. **Relay selection procedure: a) Network topology consists of source CH *s*, destination CH *d* in red circles and a number of neighbor nodes in grey circles, b) *s* broadcasts *relay_probe* message m_1 to its neighborhood, c) *d* sends *relay_probe* message m_2 as an acknowledgement, d) Neighbor nodes that successfully decode the *relay_probe* messages of both CHs send *relay_response* message m_3, e) *s* sends *relay_request* m_4 to the selected relay nodes, f) Selected relay nodes confirm the request and send *relay_confirmation* message m_5 to *s* and *d*.**

IV. RATELESS CODED RELAY SELECTION

It has been proven that cooperative strategies are energy efficient than non-cooperative direct transmission [24], [36]. However, involving more relay nodes between source and destination impose more signalling overhead and power consumption. On the other hand, the selection of the relay nodes plays a critical role to improve the performance of the cooperative system [31], [38], [41].

Considering the cost and performance issues in M2M network, we propose a relay selection algorithm called rateless coded incremental relay selection (RCIRS), aiming at achieving the given target data rate by employing minimum number of relay nodes. We consider a decode and forward relaying system where source CH transmit its information to the destination and relays using fountain codes. After successfully decoding the source CH's information, relay nodes encode the received information using fountain codes. The relay nodes and the source node then continue their transmission to the destination until the source information is successfully decoded at the destination.

A. RELAY SELECTION PROCEDURE

We illustrate our proposed relay selection procedure in Fig. 3. Fig. 3(a) shows an example network topology with a source CH and a destination CH by red colored circles, and a number of neighbor nodes by grey colored circles. In the beginning of relay selection, source CH, s broadcasts *relay_probe* message denoted by m_1 as shown in Fig. 3(b) using predefined rateless code to its neighbor nodes and continues its broadcasting until it receives an acknowledgement from destination CH, d. Let H bits of data to be broadcasted as *relay_probe* message. We assume H is a long enough number. The addresses of the source and destination CHs are included in the *relay_probe* message. After successfully decoding of m_1, d sends a *relay_probe* message denoted by m_2 as an acknowledgment to s using rateless code which is shown in Fig. 3(c). Then s estimates the end to end data rate for s-d pair based on the time it takes for the successful decoding of *relay_probe* message transmitted by d. This *relay_probe* message transmitted by d is reliably decoded at s when

$$\tau_0 C_{sd} = \tau_0 log_2(1+\gamma_{sd}) \geq H, \tag{3}$$

where τ_0 is the duration of transmission and γ_{sd} is the received SNR at s for s-d pair. In ideal fountain code, the receiver is capable to recover the source information as soon as the accumulated mutual information equal the entropy of the codeword. However it is impossible to generate "universal" fountain code that is simultaneously perfect at all possible rates. In practical fountain code, the receiver is capable to recover the source information with overhead that is not too large [28]. An overhead like this will only lead to a loss of rate and does not impact much on the analysis here. In order to simplify the analysis, ideal fountain codes and decoders are assumed at the receivers in this section. Therefore, the achievable data rate per unit bandwidth for s-d pair is given by

$$C_{sd} = log_2(1+\gamma_{sd}) = H/(\tau_0). \tag{4}$$

At the same time, neighbor nodes process the received *relay_probe* messages from different CHs and measure the achievable data rate. Let assume neighboring node r_i takes τ_{sr_i} and τ_{dr_i} time to decode *relay_probe* messages of s and d, respectively. Hence, the achievable data rate for s-r_i pair is

$$C_{sr_i} = log_2(1+\gamma_{sr_i}) = H/\tau_{sr_i}, \tag{5}$$

where γ_{sr_i} the received SNR at r_i. Similarly, the achievable data rate for r_i-d pair is given by

$$C_{r_i d} = log_2(1+\gamma_{r_i d}) = H/\tau_{r_i d}, \tag{6}$$

where $\gamma_{r_i d}$ is the received SNR at r_i for r_i-d pair. Among the neighbor nodes, only those who receive *relay_probe* messages from both source and destination CHs respond to the *relay_probe* with *relay_response*, which is denoted by m_3 as shown in Fig. 3(d). The *relay_response* message includes the data rates C_{sr_i} and $C_{r_i d}$ as well as the ids of both source and destination CHs. Source CH, s then analyzes each *relay_response* message and takes only those nodes whose source to relay data rate, C_{sr_i} are greater than C_{sd}. We refer these nodes as initial relay candidates and the set of candidate relays as initial candidate set $\mathcal{C}$.

The next step is to search for a subset $\mathcal{A}_{min}$ from the initial candidate set $\mathcal{C}$. Here, $\mathcal{A}_{min}$ denotes our desired set of relay nodes that consists of minimum number of relay nodes and contributes to meet the target CH-to-CH data rate. In regards to this, we propose a search criterion and a greedy algorithm, namely RCIRS algorithm. In the next two subsections, we explain the proposed search criterion and RCIRS algorithm. After the selection of set $\mathcal{A}_{min}$, the source sends the relay request message m_4 to the selected nodes as shown in Fig. 3(e). Then the selected nodes confirm this request and send a *relay_confirmation* message, which is denoted as m_5, to both s and d as shown in Fig. 3(f). Thus, during the design phase of the network, we judiciously select the minimum number of relay nodes from a large set of neighbor nodes. When the network starts to actively operate, the source node sends data only targeting the selected relay nodes along with the destination node. Then the selected nodes forward the source data only to the destination and thus the overall cost is reduced while the target data rate is maintained.

B. RELAY SELECTION PROBLEM

In this subsection, the relay selection criterion and RCIRS algorithm are presented. The main goal of the relay selection problem is to find a set of relay nodes $\mathcal{A}_{min}$ from $\mathcal{C}$, that has minimum number of relay nodes and also satisfies the target data rate constraint, C_{target}. To solve this problem, we establish a search criterion. In the search criterion, we introduce a parameter, namely achievable cooperative data rate, C_{cdr} that represents the data rate between source CH and destination CH attained by the co-operative participation of source, relay and destination nodes. The search criterion is stated as below:

$$C_{cdr} \geq C_{target}, \tag{7}$$

where

$$C_{cdr} = \left(\frac{C_{sd} + \sum_{r_i \in \mathcal{A}_x} C_{r_i d}}{1 + \sum_{r_i \in \mathcal{A}_x} \frac{C_{r_i d}}{C_{sr_i}}} \right), \tag{8}$$

where $\mathcal{A}_x \subseteq \mathcal{C}$ is a successful candidate set that satisfies the criterion in Eq. 7. The relationship of the parameter C_{cdr} with previously defined data rates of s-d, s-r_i and r_i-d pair shown in Eq. 8, is derived by using Eq. 4, 5, 6 and the following equation,

$$\tau.C_{sd} + \sum_{r_i \in \mathcal{A}_x} (\tau - \tau_{sr_i}) C_{r_i d} = H, \tag{9}$$

where τ is the minimum time taken by the destination to successfully decode the *relay_probe* message with the help of candidate set $\mathcal{A}_x$. It is worth noting that C_{cdr} represents the average of cooperative data rate, which has nothing to do with H. In practice, H, the number of transmitted bits, influences the start time of relay transmission. For this reason, the coded cooperative communications discussed in this paper have a weakness of inconstant data rate, i.e., the

Algorithm 1 RCIRS

```
Input: $\mathcal{C}$, $C_{target}$
Output: $\mathcal{A}_{min}$, $C_{cdr}$
 1: $C_{cdr} \leftarrow C_{sd}$, $Sum\_C_{rd} \leftarrow 0$, $Sum\_C_{rd}/C_{sr} \leftarrow 0$
 2: $\mathcal{A}_{min} \leftarrow \emptyset$
 3: while $C_{cdr} < C_{target}$ do
 4:     for each $i \in \mathcal{C} \backslash \mathcal{A}_{min}$ do the following do
 5:         $\Delta_{r_i} = \left( \frac{C_{sd} + Sum\_C_{rd} + C_{r_i d}}{1 + Sum\_C_{rd}/C_{sr} + C_{r_i d}/C_{sr_i}} \right)$
 6:     end for
 7:     $r_{i*} \leftarrow \arg\max_{i \in \mathcal{C} \backslash \mathcal{A}_{min}} \Delta_{r_i}$, $\Delta_{r_{i*}} = max(\Delta_{r_i})$
 8:     $\mathcal{A}_{min} \leftarrow \mathcal{A}_{min} \cup r_{i*}$
 9:     $C_{cdr} \leftarrow \Delta_{r_{i*}}$
10:     $Sum\_C_{rd} \leftarrow Sum\_C_{rd} + C_{r_{i*} d}$
11:     $Sum\_C_{rd}/C_{sr} \leftarrow Sum\_C_{rd}/C_{sr} + \frac{C_{r_{i*} d}}{C_{sr_{i*}}}$
12: end while
13: return $\mathcal{A}_{min}$, $C_{cdr}$
```

destination achieves higher data rate as more relays join the transmission later. Inconstant data rate may negatively affect realtime applications, such as video and audio. It is, nevertheless, not a significant problem for data collection task in M2M domain. Let consider, N is the total number of relays in the initial candidate set $\mathcal{C}$. So, the number of all possible successful candidate set $\mathcal{A}_x$ could vary from 0 to $2^N - 1$. In the next paragraph, we have shown an example problem formulation of searching $\mathcal{A}_{min}$ from set $\mathcal{C}$.

Let α_i be an indicator variable which is equal to 1 if r_i is selected as relay and 0 otherwise, the minimal selection problem can be formally defined as follows:

$$\begin{aligned} &\min \sum_{i=1}^{N} \alpha_i \\ &\text{s.t. } C_{cdr} \geq C_{target}, \\ &\quad \alpha_i \in \{0, 1\}, \quad \forall r_i \in \mathcal{C}. \end{aligned} \tag{10}$$

The above problem is a non linear integer optimization problem. Now if the size of the network is high i.e. if N is a large number, finding $\mathcal{A}_{min}$ from all possible $\mathcal{A}_x \subseteq \mathcal{C}$ sets by using conventional Brute-Force search would require huge computational effort. The computational complexity of BFS increases exponentially with the number of relay candidates N, that limits its application in practical systems. With N initial relay candidates in the selection process, an exponential complexity of $2^N - 1$ would be required to find out $\mathcal{A}_{min}$ set. In order to reduce the computational complexity of searching $\mathcal{A}_{min}$, we propose a greedy algorithm RCIRS in the next subsection.

C. RATELESS CODED INCREMENTAL RELAY SELECTION (RCIRS) ALGORITHM

In Algorithm 1, different steps of RCIRS algorithm is depicted. The basic idea of RCIRS algorithm is that nodes in the set $\mathcal{C}$ are included in cooperative group one by one so that the cooperative data rate is incrementally increased until the condition in Eq. 7 is satisfied. In order to minimize the number of relays, each time the candidate that makes the maximum increment to C_{cdr} is added in the cooperative group. At the beginning, selected $\mathcal{A}_{min}$ is an empty set, since no relay has been selected, and C_{cdr} is initialized with C_{sd} by considering the signal received from only s (line 1-2). After the initializations, C_{cdr} is compared with C_{target} (line 3). If C_{cdr} is smaller than C_{target}, the achievable cooperative data rate Δ_{r_i} is computed by using each candidate relay r_i (line 4-6). Then the candidate relay that maximizes Δ_{r_i} is selected and included in the selected relay set $\mathcal{A}_{min}$ (line 7-8). C_{cdr}, Sum_C_{rd} and Sum_C_{rd}/C_{sr} are updated accordingly (line 9-11). This process is repeated for remaining elements of $\mathcal{C}$ until Eq. 7 is satisfied (line 12). At the end, the algorithm returns the desired relay set $\mathcal{A}_{min}$ and cooperative data rate of the system C_{cdr} (line 13). In this way, the RCIRS algorithm finds a near minimal $\mathcal{A}_{min}$ by limiting the candidate search space within $N + (N-1) + \ldots.1 = N(N+1)/2$ sets, which is much lower than the search space of BFS $(2^N - 1)$.

V. FOUNTAIN CODED COOPERATIVE PROTOCOLS

We propose two fountain coded cooperative communication protocols, namely source-feedback and non-source-feedback where source CH and relay nodes use their own fountain routines to encode information and then transmit to the destination through different orthogonal channels. We assume that the decoder knows the encoding degree distribution of received encoded symbols via an extra robust direct sequence spread spectrum (DSSS) channel with long sequence length. This is different from using identical random number generator at both encoder and decoder as in [31], which needs strict synchronization and increases the complexity in a multiple relay network.

A. SOURCE-FEEDBACK BASED PROTOCOL (SF-PROTOCOL)

In this protocol, a source CH encodes its information using fountain code and transmits to the destination CH and relays. Relay nodes attempt to decode source data and forward the source information to the destination CH using their own fountain codes as soon as the information is decoded successfully at the relay nodes. Source CH selects this relay nodes by appropriate relay selection algorithm. Both source CH and relays then continue their transmissions until they receive an acknowledgment from the destination CH indicating that the reception has been successful. The protocol works as follows:

1) The source transmits its encoded data targeting the destination and relays.
2) Both relays and destination accumulate information from source transmission.
3) Since the source to relay link is superior than source to destination link, relays decode the information faster than the destination. After successfully decoding the source information, relay nodes co-operate with the source to transmit to the destination. Each relay uses

its own fountain encoding routine to encode information and then transmit to the destination through pre-allocated orthogonal channel.

4) The destination collects information from both source and relays, and attempts to decode information once the accumulated mutual information is slightly greater than the source information. If the decoding is successful, then it sends an ACK targeting the source and relays. Otherwise it continues to collect more information. This procedure continues until successful reception at the destination.

B. NON-SOURCE-FEEDBACK BASED PROTOCOL (NSF-PROTOCOL)

In this protocol, source CH transmits the data stream encoded by a fountain codes targeting the destination and relay nodes. The relay nodes listen to the source data; as soon as a relay acquired sufficient information to decode source data, it transmits an ACK to the source that its reception was successful. Instantly the relay node switches from reception to transmission mode and co-operates with the source to transmit to the destination. Once the source has received acknowledgments from all of the relay nodes, it ceases its transmission hoping that the destination can successfully receive the remaining information from relays. The protocol works as follows:

1) Source generates a large number of encoded symbols and transmit its encoded data targeting the destination and relays.
2) Relays and the destination d consistently receive signals from source and accumulate the mutual information to decode the source information.
3) As soon as a relay node has sufficient information to decide on a codeword, it sends acknowledgement to the source and switches from reception mode to transmission mode. At this point, it encodes information using its own fountain encoding routine and transmit on the pre-allocated orthogonal channel.
4) Source ceases its transmission after receiving acknowledgement from all relay nodes. The suspension of source nodes may help to decrease the energy consumption. By this time, if the destination d can not accumulate enough partial information from source transmission, it depends on the relay nodes to collect the remaining information. After successfully decoding of source information, the destination sends ACK to relays.

C. ENCODING AND DECODING OF RAPTOR CODE

In our proposed cooperative protocols, the source and relays use a special class of fountain code, namely Raptor code to encode their information. Raptor code is universally capacity achieving over the binary erasure channel (BEC) [27] and nearly capacity-achieving over other channel models such as binary symmetric channels (BSC), AWGN and fading channels [28], [29]. It is a concatenation of two codes, a pre-code or outer code and an inner code. Usually LDPC and LT codes are used as outer and inner codes, respectively. However, in most practical settings Raptor codes outperform LT-codes in every aspect.

$$\begin{aligned}\Omega(x) = {} & 0.006x + 0.492x^2 + 0.03396x^3 + 0.2403^4 \\ & + 0.006^5 + 0.096x^8 + 0.049x^{14} + 0.018x^{30} \\ & + 0.0356x^{33} + 0.033x^{200}. \qquad (11)\end{aligned}$$

We assume source CH s wants to transmit k-symbols information block to destination CH d. In Raptor encoding, the k-symbols information $\{x = x_1, x_2, ...x_k\}$ is first encoded by the pre-code which is typically high-rate LDPC code to produce a k'-input symbols $\{v = v_1, v_2, ...v_{k'}\}$. Then LT-codes that follows the degree distribution as mentioned in Eq. 11 [27] is applied to v to create Raptor codeword $\{c = c_1, c_2, ...c_m....\}$. In our system, A rate-0.98 LDPC code is implemented as the outer code of Raptor codes. In Fig. 4, the factor graph of Raptor code is shown that is referred as G_m and truncated at block length m where channel output $\{y = y_1, y_2, ...y_m\}$ corresponds to transmitted Raptor codeword $\{c = c_1, c_2, ...c_m\}$.

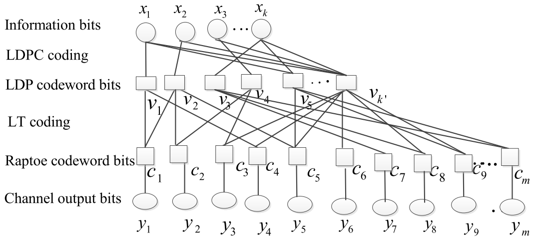


FIGURE 4. The factor graph of Raptor code. The graph is truncated to length *m*.

As mentioned before, the degree of the encoded information is transmitted to the destination by an extra robust CDMA channel with long sequence length. The decoder collects information progressively and makes first decoding attempts when the received accumulated information is little bit larger than the source information. In noisy channel, the decoding of raptor code is accomplished using the standard Belief Propagation (BP) algorithm. At the l^{th} decoding attempt, it performs BP decoding on factor graph G_m by iteratively passing the LLR (log-likelihood ratio) messages from input bits$\{v_1...v_{k'}\}$ to output bits $\{c_1...c_m\}$ and then from output bits back to input bits. Let $\mu^{j,l}_{c_o,v_i}$ and $v^{j,l}_{v_i,c_o}$ denote the message passed from the output bit c_o to the input bit v_i and input bit v_i to the output bit c_o, respectively at the j^{th} iteration of l^{th} decoding attempt. In every iteration, the following message update rules are applied in parallel to all input and output nodes in the factor graph [27]

$$\tanh\frac{\mu^{(j,l)}_{c_o,v_i}}{2} = \tanh\frac{(Z_{c_o})}{2}\prod_{i'\neq i}\tanh\frac{v^{j,l}_{v_i,c_o}}{2}, \qquad (12)$$

$$v^{(j+1,l)}_{v_i,c_o} = \sum_{o'\neq o}\mu^{(j,l)}_{c_{o'},v_i}, \qquad (13)$$

where Z_{c_o} is log-likelihood ratios (LLR) of the transmitted bit c_o. Since we use binary phase shift keying (BPSK) as modulation scheme, the transmitted codeword $c_o \in 0, 1$ is of equal probability. In Rayleigh fading channel, the channel intrinsic log likelihood information corresponding to the output node c_o while channel state information is available at the receiver, is formulated as [44]

$$Z_{c_o} = \log \frac{pr(y_o|c_o = 0)}{pr(y_o|c_o = 1)} = \frac{2}{\sigma^2} y_o.a, \tag{14}$$

where $\sigma^2 = \frac{P_0}{\sigma_0^2}$, y_o is the noisy observation of the channel and a is the normalized Rayleigh fading factor with $E[a^2] = 1$ and density function $f(a) = 2a\exp(-a^2)$.

In the end of l^{th} decoding attempt, if the transmitted codeword is decoded correctly, the receiver sends an ACK through a noiseless feedback channel to the source to terminate the transmission of the current code word. Otherwise it collects more output symbols and attempts again to decode the codeword.

D. TRANSMISSION EFFICIENCY

In rateless coded system, the source node generates a large number of symbols and transmits to the destination until it receives any ACK from the destination. Hence, the probability of outage is always driven to zero unless any constraint is imposed on decoding delay. In this paper, transmission efficiency rather than outage probability is considered as a primary metric to evaluate the performance of the proposed protocols. In the following, we evaluate the performance of our proposed protocols based on the required time to decode the source information correctly at destination.

Let n denotes the number of time slots required for the destination to collect enough information from all source and relays before it successfully decodes a k-bits source message. In this work, we use BPSK modulation. BPSK allows transmission of one bit per channel that means a time slot is what a transmitter takes to transmit 1 bit. Therefore, the transmission efficiency is given by $\zeta = k/n$ where the number of required time slots are normalized by the bit rate. Since the data rates of source-relay link are greater than the data rate of source-destination link, relay nodes can decode the source information faster than the destination. The source information is decoded at relay r_j once the accumulated information satisfies

$$n_j^{sr} C_{sr_j} \geq k, \tag{15}$$

where n_j^{sr} is the required time slots for r_j to decode source information correctly. Since BPSK is used as modulation, the data rate, C_{ab} of a link, a-b can be calculated by [17]:

$$C_{ab}^{BPSK} = 1 - \frac{1}{2\sqrt{2\pi\gamma_{ab}}} \int_{-\infty}^{\infty} log_2(1 + e^{-x}) e^{-\frac{x - 2\gamma_{ab}}{2\gamma_{ab}}} dx, \tag{16}$$

where $\gamma_{ab} = |H_{ab}|^2 P_a / \sigma_b^2$. In both protocols, as soon as the relay decodes source information, it encodes the receive information using fountain codes and transmit through the pre-assigned orthogonal channel to the destination. In source-feedback protocol, the source node continues its transmission until the receiver successfully decodes the source information. Using BPSK as modulation scheme, in this protocol the destination correctly decode the source information when the accumulated information satisfies

$$nC_{sd}^{BPSK} + \sum_{j=1}^{R} (n - n_j^{sr}) C_{r_j d}^{BPSK} \geq k, \tag{17}$$

where, R is the number of participating relay nodes, C_{sd} is the data rate of s-d link and $C_{r_j d}$ is the data rate of r_i-d link. Restricting the modulation scheme to BPSK, the maximum achievable transmission efficiency ζ^* of this protocol can be defined as

$$C_{sd}^{BPSK} + \sum_{j=1}^{R} (1 - \frac{n_j^{sr}}{n}) C_{r_j d}^{BPSK} = \zeta^*. \tag{18}$$

In non-source-feedback protocol, the source node ceases its transmission after all relay nodes successfully decode source information. Relay nodes transmit towards the destination until the source information is successfully decoded at the destination. Therefore, in non-source-feedback protocol, the destination may reliably decode the source information when the accumulated information satisfies

$$max\ n^{sr} C_{sd}^{BPSK} + \sum_{j=1}^{R} (n - n_j^{sr}) C_{r_j d}^{BPSK} \geq k, \tag{19}$$

where $max\ n^{sr} = max\{n_1^{sr}, n_2^{sr}, \ldots n_R^{sr}\}$ is the required time for the relay that has minimum source to relay data rate, $min\ C^{sr} = min\{C_{sr_1}, C_{sr_2}, \ldots C_{sr_R}\}$. The maximum transmission efficiency, ζ^* of this protocol can be defined as

$$\frac{max\ n^{sr}}{n} C_{sd}^{BPSK} + \sum_{j=1}^{R} (1 - \frac{n_j^{sr}}{n}) C_{r_j d}^{BPSK} = \zeta^*. \tag{20}$$

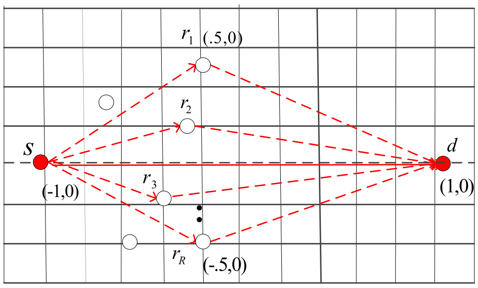


FIGURE 5. **Simulation model.**

VI. SIMULATION RESULTS

The simulation scenario in our study consists of a pair of source CH and destination CH with a number of relay candidates where nodes are placed randomly within the area $-1 \leq x \leq 1$, $-.5 \leq y \leq .5$. The source is placed at $(-1, 0)$ and the destination is at $(1, 0)$ as shown in Fig. 5.

For simplicity, the gaussian noise at each node is assumed to be of the same variance σ_0^2, and each node has similar transmit power P_0. Without loss of generality, we assume a unit path loss between source and destination, i.e., $G_{sd} = 1$. We then have $G_{sr_i} = \left(\frac{d_{sd}}{d_{sr_i}}\right)^{\alpha}$ and $G_{r_id} = \left(\frac{d_{sd}}{d_{r_id}}\right)^{\alpha}$ where d_{sd}, d_{sr_i} and d_{r_id} are the distances between source and destination, source and i^{th} relay node r_i, and destination and r_i, respectively. We assume free-space path loss, so we have $\alpha = 2$.

A. PERFORMANCE OF RELAY SELECTION ALGORITHM

In this subsection, we conduct simulations to evaluate the performance of the proposed relay selection algorithm. The channels between all nodes are assumed to be frequency-flat block-fading Rayleigh channels. We compare our relay selection method with source relay channel based relay selection (SRCRS) as in [36] and [40] where relay nodes are selected based on the channel quality between source and relays without considering the relays and destination links.

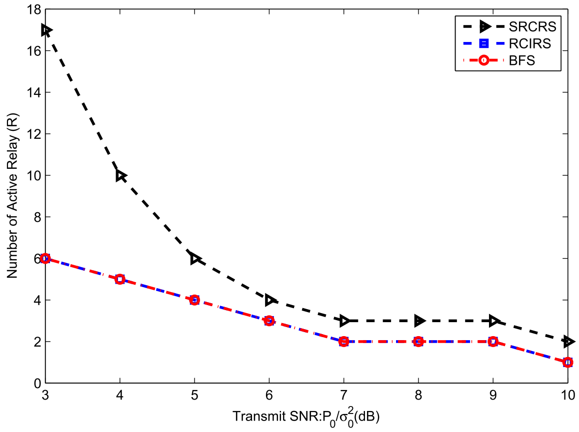


FIGURE 6. **Number of active relays vs transmit SNR(dB) ($N = 25$, $C_{target} = 4$ bits/sec).**

Fig. 6 shows the number of active relays as a function of transmit SNR, P_0/σ_0^2 for three schemes including RCIRS, SRCRS and BFS having a data rate constraint, $C_{target} = 4\ bits/sec$. We assume $N = 25$. Nodes that participate in the cooperative group until the destination is able to decode the *relay_probe* message are defined as active relays. From Fig. 6, it is observed that SRCRS employs more relay nodes than RCIRS to meet the target data rate. This is because in SRCRS, node is included in the cooperative group as soon as it decodes the source information successfully with the possibility of having poor link towards destination. It is also observed that RCIRS employs equal number of relays as BFS to meet the data rate requirements with less computation complexity. Moreover, it is shown that at lower transmit SNR region, a large number of relays are required to meet the data rate requirements, which decreases gradually at higher SNR region.

Fig. 7 shows the cooperative data rate vs transmit SNR, P_0/σ_0^2 for different schemes with parameters, $R = 4$ and $N = 25$. It is observed that RCIRS almost attains the performance of BFS as expected and outperforms the SRCRS. This is because in RCIRS, node is added in the cooperative group based on the data rate of source to relay and relay to destination links while in SRCRS, only the data rate of source to relay is considered.

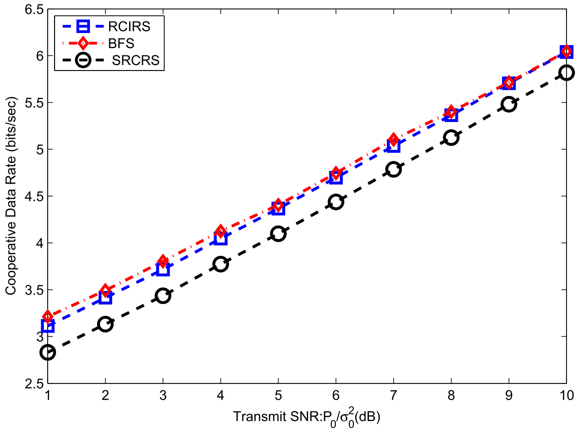


FIGURE 7. **Cooperative data rate vs transmit SNR(dB) ($N = 25$, $R = 4$).**

TABLE 2. **Comparison among different relay selection methods ($N = 25$).**

$P_0/\sigma_0^2(dB)$	Method	C_{cdr} (bits/sec)	R
4	BFS	4.1996	8
	RCIRS	4.1812	8
	SRCRS	4.1996	24
8	BFS	5.4882	7
	RCIRS	5.4799	7
	SRCRS	5.4882	20

Table 2 lists the maximum achievable cooperative data rate, C_{cdr} and corresponding number of active relay nodes, R for different value of P_0/σ_0^2 and number of initial relay candidates, $N = 25$. It is noted that SRCRS achieves the same C_{cdr} as BFS by employing more number of relay nodes than that of the BFS. BFS maximizes C_{cdr} by employing minimum number of relay nodes with the cost of huge computation complexity (e.g., $2^{25} - 1$). It is worth noting that our proposed RCIRS almost attain the C_{cdr} of BFS by employing the same number of relay nodes as of BFS with less computational complexity. At $P_0/\sigma_0^2 = 8\ dB$, the achievable cooperative data rate of RCIRS is 5.4799 bits/sec, which is only 0.15% less than that of BFS.

B. PERFORMANCE OF FOUNTAIN CODED COOPERATIVE PROTOCOLS

In this subsection, we compare the performance of the proposed fountain coded cooperative protocols under different relay selection methods with that of noncooperative direct communication scheme.

Fig. 8 presents the performance of the noncooperative direct transmission (DT) and proposed protocols in terms of transmission efficiency, ζ as a function of transmit SNR, P_0/σ_0^2 under different relay selection methods for

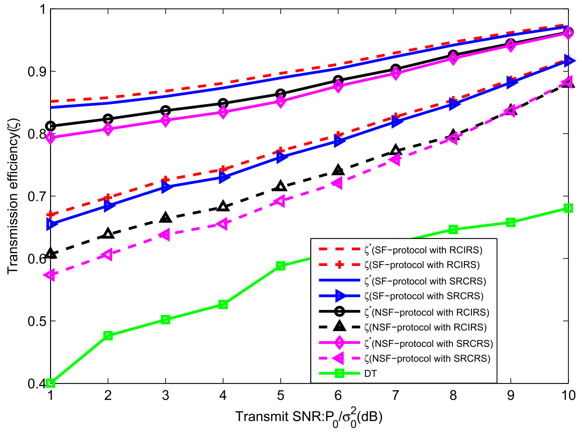


FIGURE 8. **Transmission efficiency vs transmit SNR in Rayleigh channel.**

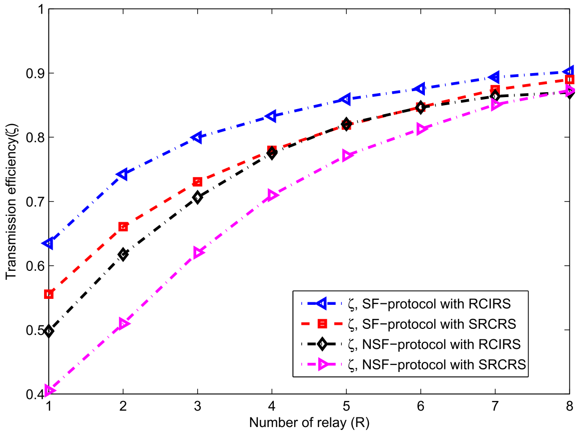


FIGURE 9. **Transmission efficiency vs number of relay in Rayleigh channel.**

parameter $R = 2$. It is observed that cooperative protocols dramatically improve the transmission efficiency than DT between two neighboring CHs. It is observed that at fixed relay selection method the source-feedback based protocol (SF-protocol) outperforms the non-source-feedback based protocol (NSF-protocol). The reason of the better performance of SF-protocol, is that in this protocol relays and source continue their transmission until the destination sends back an ACK, whereas in NSF-protocol, the source stops its transmission after the relay nodes decode the message successfully. It is also observed that the relay selection methods significantly influence the performance of the protocols. The proposed protocols (SF/NSF-protocol) using RCIRS outperforms its SRCRS counterpart. Furthermore, the impact of relay selection method is more noticeable on NSF-protocols than SF-protocols. It is observed that at $P_0/\sigma_0^2 = 1dB$, the performance gap between SF-protocol using RCIRS and SF-protocol using SRCRS is 2.22% while the performance gap between NSF-protocol using RCIRS and NSF-protocol using SRCRS is 5.45%. This is because in the SRCRS method, relay nodes are selected based on the source-relay link without considering the relay-destination link. Therefore, the possibility of having poor relay-destination link of the selected relay nodes and the suspension of the source transmission in NSF-protocol, significantly degrade the performance of the NSF-protocol using SRCRS.

The maximum achievable transmission efficiency, ζ^* of both protocols under different relay selection methods are also presented in Fig. 8. It is observed as transmit SNR increases, the ζ^* curve reaches the asymptote of 1, due to the BPSK modulation scheme. Comparing the achieved transmission efficiency, ζ with the maximum achievable transmission efficiency, ζ^* for either protocol, we notice that there is an obvious rate loss, which is due to the suboptimality of the Raptor codes. As shown in the figure, at $P_0/\sigma_0^2 = 10 \quad dB$ under RCIRS method the rate loss of SF-protocol and NSF-protocol are 5.7% and 9%, respectively.

In Fig. 9, we illustrate the transmission efficiency of the proposed protocols as a function of R for fixed transmit SNR, $P_0/\sigma_0^2 = 6 \quad dB$. Here also relay selection methods influence the performance of the protocols in terms of transmission efficiency ζ. We observe that SF-protocols using RCIRS method outperforms the SF-protocols using SRCRS method. We also observe that the performance of the protocols always improves with the involvement of more relays. However, at fixed SNR, the performance difference of proposed protocols at a fixed relay selection method gradually decrease with the increase of relay nodes as shown in Fig. 9. This is because, more relays render more mutual information to destination and reduces the impact of direct link at destination.

VII. CONCLUSION

Reliability of M2M networks is getting more attention as an important IoT performance indicator. With respect to this fact, this paper develops fountain coded cooperative schemes and investigates their performance in clustered M2M networks. Particularly, we first propose an RCIRS algorithm to judiciously select relay nodes so that the required data rate is achieved with the minimum number of participating relays. Our proposed relay selection algorithm best suits for adaptive systems in which the data rate between two clusters can be adjusted to attain the required end to end data rate to ensure quality of services of the systems. It shows that our proposed RCIRS employs less relay nodes than SRCRS and nearly attains the cooperative data rate obtained by BFS. We then develop source-feedback and non-source-feedback based protocols to improve the data transmission between two neighboring CHs. Regardless of the protocol used, transmission efficiency can always be improved by involving more relay nodes for cooperation at the cost of additional complexity. Simulation results demonstrate that our design can significantly improve the end-to-end performance between two CHs than that of non cooperative direct transmission. It is also observed that at fixed relay selection method, the source-feedback based protocol (SF-protocol) always outperforms the non-source-feedback (NSF-protocol) one in terms of transmission efficiency.

REFERENCES

[1] G. Kortuem, F. Kawsar, D. Fitton, and V. Sundramoorthy, "Smart objects as building blocks for the Internet of Things," *IEEE Internet Comput.*, vol. 14, no. 1, pp. 44–51, Jan./Feb. 2010.

[2] G. N. Shirazi, "Optimization in wireless sensor and machine-type communication networks," Ph.D. dissertation, Dept. Electr. Comput. Eng., British Columbia Univ., Vancouver, BC, Canada, 2006.

[3] J. Chen, X. Cao, P. Cheng, Y. Xiao, and Y. Sun, "Distributed collaborative control for industrial automation with wireless sensor and actuator networks," *IEEE Trans. Ind. Electron.*, vol. 57, no. 12, pp. 4219–4230, Dec. 2010.

[4] S.-Y. Lien, T.-H. Liau, C.-Y. Kao, and K.-C. Chen, "Cooperative access class barring for machine-to-machine communications," *IEEE Trans. Wireless Commun.*, vol. 11, no. 1, pp. 27–32, Jan. 2012.

[5] Y. Zhang, R. Yu, S. Xie, W. Yao, Y. Xiao, and M. Guizani, "Home M2M networks: Architectures, standards, and QoS improvement," *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 44–52, Apr. 2011.

[6] Y. Zhang, R. Yu, M. Nekovee, Y. Liu, S. Xie, and S. Gjessing, "Cognitive machine-to-machine communications: Visions and potentials for the smart grid," *IEEE Netw.*, vol. 26, no. 3, pp. 6–13, May/Jun. 2012.

[7] "Requirements related to technical system performance for imt- advanced radio interface(s) [imt.tech]," Int. Telecommun. Union, Paris, France, Tech. Rep. M.2134-0 (2008), 2008.

[8] P. Bhat *et al.*, "LTE-advanced: An operator perspective," *IEEE Commun. Mag.*, vol. 50, no. 2, pp. 104–114, Feb. 2012.

[9] Machina Research. (2013). *Machine-to-Machine Connections to Hit 18 Billion in 2022 Generating USD1.3 Trillion Revenue*. [Online]. Available: https://machinaresearch.com/news/archive/2013/12/

[10] Exalted Project. (Aug. 2011). *First Report on LTE-M Algorithms and Procedures*. [Online]. Available: http://www.ict-exalted.eu

[11] K.-R. Jung, A. Park, and S. Lee, "Machine-type-communication (MTC) device grouping algorithm for congestion avoidance of MTC oriented LTE network," in *Proc. 1st Int. Conf. Secur.-Enriched Urban Comput. Smart Grid (SUComS)*, Daejeon, Korea, Sep. 2010, pp. 167–178.

[12] R. M. Huq, K. P. Moreno, H. Zhu, J. Zhang, O. Ohlsson, and M. I. Hossain, "On the benefits of clustered capillary networks for congestion control in machine type communications over LTE," in *Proc. 24th Int. Conf. Comput. Commun. Netw. (ICCCN)*, Aug. 2015, pp. 1–7.

[13] A. Scaglione, D. L. Goeckel, and J. N. Laneman, "Cooperative communications in mobile ad hoc networks," *IEEE Signal Process. Mag.*, vol. 23, no. 5, pp. 18–29, Sep. 2006.

[14] Z. Zhu, L. Zhang, and R. Wakikawa, "Supporting mobility for Internet cars," *IEEE Commun. Mag.*, vol. 49, no. 5, pp. 180–186, May 2011.

[15] E. Ekici, Y. Gu, and D. Bozdag, "Mobility-based communication in wireless sensor networks," *IEEE Commun. Mag.*, vol. 44, no. 7, pp. 56–62, Jul. 2006.

[16] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[17] Y. Zhang and Z. Zhang, "Joint network-channel coding with rateless code over multiple access relay system," *IEEE Trans. Wireless Commun.*, vol. 12, no. 1, pp. 320–332, Jan. 2013.

[18] A. Nessa, M. Kadoch, and B. Rong, "Joint network channel fountain scheme for reliable communication in wireless networks," in *Proc. IEEE ICNC*, Feb. 2014, pp. 206–210.

[19] A. Nessa and M. Kadoch, "Joint network channel fountain schemes for machine-type communications over LTE-advanced," *IEEE Internet Things J.*, vol. 3, no. 3, pp. 418–427, Jun. 2016.

[20] Q. Li, R. Q. Hu, Y. Qian, and G. Wu, "Cooperative communications for wireless networks: Techniques and applications in LTE-advanced systems," *IEEE Wireless Commun.*, vol. 19, no. 2, pp. 22–29, Apr. 2012.

[21] H. Ochiai, P. Mitran, H. V. Poor, and V. Tarokh, "Collaborative beamforming for distributed wireless ad hoc sensor networks," *IEEE Trans. Signal Process.*, vol. 53, no. 11, pp. 4110–4124, Nov. 2005.

[22] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 6, pp. 1089–1098, Aug. 2004.

[23] R. Madan, N. B. Mehta, A. F. Molisch, and J. Zhang, "Energy-efficient cooperative relaying over fading channels with simple relay selection," *IEEE Trans. Wireless Commun.*, vol. 7, no. 8, pp. 3013–3025, Aug. 2008.

[24] Z. Zhou, S. Zhou, S. Cui, and J.-H. Cui, "Energy-efficient cooperative communication in a clustered wireless sensor network," *IEEE Trans. Veh. Technol.*, vol. 57, no. 6, pp. 3618–3628, Nov. 2008.

[25] M. Dohler, Y. Li, B. Vucetic, A. H. Aghvami, M. Arndt, and D. Barthel, "Performance analysis of distributed space-time block-encoded sensor networks," *IEEE Trans. Veh. Technol.*, vol. 55, no. 6, pp. 1776–1789, Nov. 2006.

[26] M. Luby, "LT codes," in *Proc. 43rd Ann. IEEE Symp. Found. Comput. Sci.*, Nov. 2002, pp. 271–280.

[27] O. Etesami and A. Shokrollahi, "Raptor codes on binary memoryless symmetric channels," *IEEE Trans. Inf. Theory*, vol. 52, no. 5, pp. 2033–2051, May 2006.

[28] O. Etesami, M. Molkaraie, and A. Shokrollahi, "Raptor codes on symmetric channels," in *Proc. IEEE Int. Symp. Inf. Theory*, Jun./Jul. 2004, p. 39.

[29] J. Castura and Y. Mao, "Rateless coding and relay networks," *IEEE Signal Process. Mag.*, vol. 24, no. 5, pp. 27–35, Sep. 2007.

[30] A. Chaoub and E. Ibn-Elhaj, "Multimedia transmission over cognitive radio networks using decode-and-forward multi-relays and rateless coding," in *Proc. 4th ComNet*, Mar. 2014, pp. 1–5.

[31] X. Liu and T. J. Lim, "Fountain codes over fading relay channels," *IEEE Trans. Wireless Commun.*, vol. 8, no. 6, pp. 3278–3287, Jun. 2009.

[32] A. Nessa, M. Kadoch, R. Q. Hu, and B. Rong, "Towards reliable cooperative communications in clustered ad hoc networks," in *Proc. IEEE GLOBECOM*, Dec. 2012, pp. 4090–4095.

[33] Z. Yang and A. Host-Madsen, "Rateless coded cooperation for multiple-access channels in the low power regime," in *Proc. IEEE ISIT*, Jul. 2006, pp. 967–971.

[34] J. Abouei, S. F. Dehkordy, K. N. Plataniotis, and S. Pasupathy, "Raptor codes in wireless body area networks," in *Proc. IEEE 22nd PIMRC*, Sep. 2011, pp. 2143–2147.

[35] R. Nikjah and N. C. Beaulieu, "Low complexity selection cooperation techniques using information accumulation in dual-hop relaying networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 5, pp. 1514–1526, May 2011.

[36] A. F. Molisch, N. B. Mehta, J. S. Yedidia, and J. Zhang, "Performance of fountain codes in collaborative relay networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 11, pp. 4108–4119, Nov. 2007.

[37] Y. Zhao, R. Adve, and T. J. Lim, "Improving amplify-and-forward relay networks: Optimal power allocation versus selection," *IEEE Trans. Wireless Commun.*, vol. 6, no. 8, pp. 3114–3123, Aug. 2007.

[38] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.

[39] F. A. Onat, A. Adinoyi, Y. Fan, H. Yanikomeroglu, J. S. Thompson, and I. D. Marsland, "Threshold selection for SNR-based selective digital relaying in cooperative wireless networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 11, pp. 4226–4237, Nov. 2008.

[40] Z. Bali, W. Ajib, and H. Boujemaa, "Distributed relay selection strategy based on source-relay channel," in *Proc. IEEE 17th Int. Conf. Telecommun. (ICT)*, Apr. 2010, pp. 138–142.

[41] J. Zhang, H. Zhuang, Z. Luo, and Y. Li, "Opportunistic relay selection for rateless-coded cooperative relaying," in *Proc. CHINACOM*, Aug. 2010, pp. 1–5.

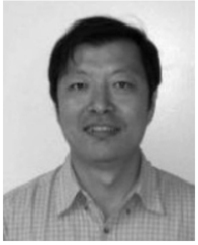
[42] H. Zhu and J. Wang, "Chunk-based resource allocation in OFDMA systems—Part I: Chunk allocation," *IEEE Trans. Commun.*, vol. 57, no. 9, pp. 2734–2744, Sep. 2009.

[43] H. Zhu and J. Wang, "Chunk-based resource allocation in OFDMA systems—Part II: Joint chunk, power and bit allocation," *IEEE Trans. Commun.*, vol. 60, no. 2, pp. 499–509, Feb. 2012.

[44] J. Hou, P. H. Siegel, and L. B. Milstein, "Performance analysis and code optimization of low density parity-check codes on Rayleigh fading channels," *IEEE J. Sel. Areas Commun.*, vol. 19, no. 5, pp. 924–934, May 2001.

AHASANUN NESSA (S'16) received the M.Eng. degree in information technology and telecommunications engineering from INHA University, South Korea, in 2009. She is currently pursuing the Ph.D. degree in electrical engineering with the Ecole de technologie superieure, Universite du Quebec, Canada. Her research interests include massive MIMO, 5G millimeter wave, cooperative communications, Internet of Things, cloud computing, and M2M communications.

MICHEL KADOCH (S'86–M'91–SM'04) received the Ph.D. degree from Concordia University in 1992. He is currently a Full Professor with the Ecole de technologie superieure, University of Quebec, Montreal. He has authored a book entilted *Protocoles et réseaux locaux : Accès à Internet* (PUQ Press, 2012). He has established the Research Laboratory Laboratoire de gestion informatique et de telecommunication which performs research on data communication networking. His current research stems from 5G, SON LTE, HetNet, WMN, and resource allocation to performance analysis. He served as a TPC Member and an Editor. He is also an Adjunct Professor with Concordia University, Montreal. He has been holding the position of the director of the M.Eng. program since 2001. He is supervising post doctorates, Ph.D. and master students, and undergraduate students with the Laboratory. His fields of interest are multicast, wireless networking, traffic engineering, and performance analysis.



BO RONG (M'07) received the B.S. degree from Shandong University, Jinan, China, in 1993, the M.S. degree from the Beijing University of Aeronautics and Astronautics, Beijing, China, in 1997, and the Ph.D. degree from the Beijing University of Posts and Telecommunications, in 2001. He is currently a Research Scientist with the Communications Research Center Canada, Ottawa, ON. He is also an Adjunct Professor with the Ecole de technologie superieure, Universite du Quebec, Canada. He has authored or co-authored over 100 technical papers in major journals and conferences, and two book chapters in wireless networkingand communications. Many of these publications have theoretical and practical significance to the research community and industry. His research interests include modeling, simulation, and performance analysis of next generation wireless networks. He is a member of the IEEE Communications Society and the IEEE Broadcasting Society. He serves as an Associate Editor of the IEEE COMMUNICATIONS LETTERS and a Guest Editor of the special issues of the IEEE COMMUNICATIONS MAGAZINE, the IEEE WIRELESS COMMUNICATIONS MAGAZINE, and the IEEE INTERNET of THINGS JOURNAL.

• • •