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A Study Of Cooperative Spectrum Sharing Schemes For Internet Of Things Systems

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A Study of Cooperative Spectrum Sharing Schemes for Internet of Things Systems

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ABSTRACT

The Internet of Things (IoT) has gained much attention in recent years with the massive increase in the number of connected devices. Cognitive Machine-to-Machine (CM2M) communications is a hot research topic in which a cognitive dimension allows M2M networks to overcome the challenges of spectrum scarcity, interference, and green requirements. In this paper, we propose a Generalized Cooperative Spectrum Sharing (GCSS) scheme for M2M communication. Cooperation extends the coverage of wireless networks as well as increasing their throughput while reducing the energy consumption of the connected low power devices. We study the outage performance of the proposed GCSS scheme for M2M system and derive exact expressions for the outage probability. We also analyze the effect of varying transmission powers on the performance of the system.

DEDICATION

To Dania, my love, because of her continuous support and motivation during the writing of this dissertation. Her love, support, and encouragement during the writing process that took several months was amazing. She was there for me at very tough times and made it much more pleasant. With her help and support, I was able to overcome many obstacles that I was running into one after another at that time. Without her you wouldn't be reading this dissertation now. I was blessed to have her in my life during this time.

To my mother, my first teacher who never gave up on me. I remember calling her at nights when life was beyond stressful until I fell asleep.

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CHAPTER 1

Cooperative Diversity Networks

1.1 Cooperative Diversity Networks Overview

Signals in wireless networks suffer from fading arising from multipath propagation, this fading can be mitigated using diversity. We are mainly interested in spatial diversity, or multiple-antenna diversity which is achieved using multiple transmitter antennas (transmit diversity) and/or multiple receiving antennas (reception diversity). Spatial diversity is attractive since it can be combined with other diversity techniques like time and frequency diversity. Cooperative diversity offers spatial diversity by creating a virtual array through distributed transmission from antennas belonging to multiple terminals.

Cooperative communications refer to systems or techniques in which users transmit each others messages to the destination. In most cases, cooperative transmissions are done over two phases. The first phase is the coordination or broadcasting phase, in which the users exchange their own source signals with each other and/or the destination. The second phase is the cooperation or forwarding phase. In this phase the users retransmit the messages to the destination. A basic cooperation system consists of two users transmitting to a common destination, as illustrated in Fig. 1.1. One of the two users acts as the source while the other user serves as the relay. In the broadcasting phase (i.e., Phase I), the source user broadcasts its data to both the relay and the destination. In the forwarding phase (i.e., Phase II), the relay forwards the sources data to the destination. The two users may interchange their roles as source and relay at different instants in time.

The basic idea of cooperative diversity is that we don't only use the direct transmission from the source to the destination, but we also use other intermediate nodes to enhance the

Network.png

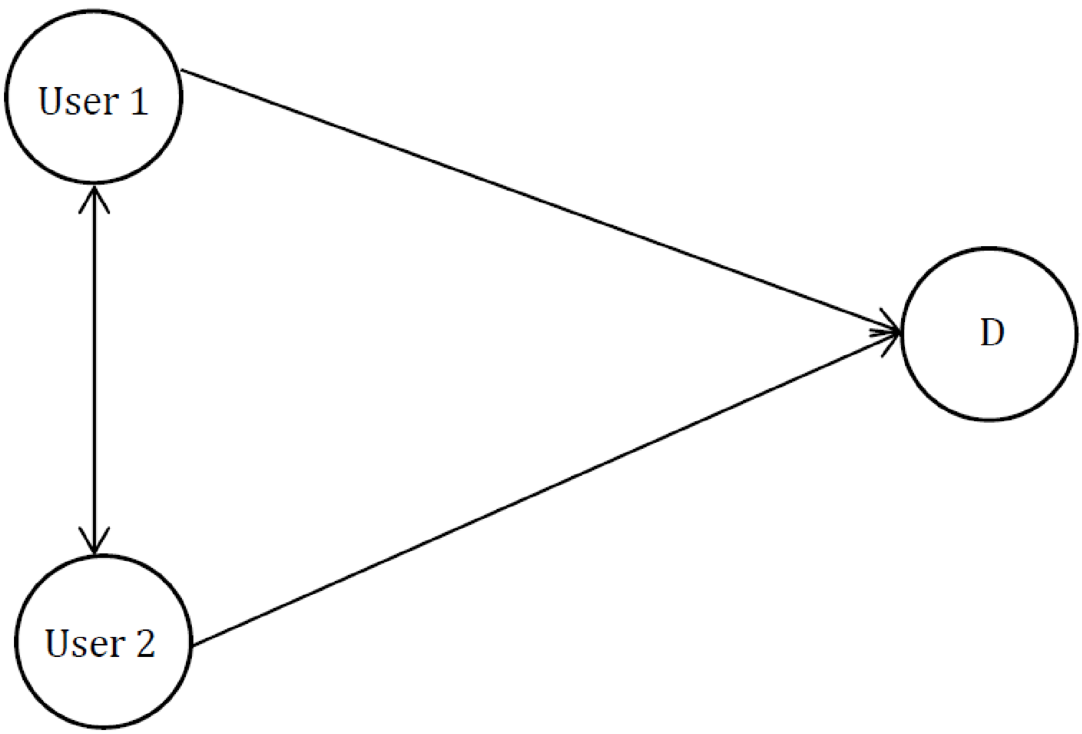

Figure 1.1. Illustration of the cooperative-diversity network

diversity by relaying the source signal to the destination. The are two main advantages of this technology; the low transmit Radio Frequency (RF) power requirements, and the spatial diversity gain

1.2 Fixed Relaying Techniques

In fixed relaying schemes all the relays in the system will forward the source message to the destination without considering the channel conditions. Many cooperation strategies have been proposed in the literature based on different relaying techniques. The most widely studied relaying techniques are: decode-and-forward (DF) and amplify-and-forward (AF).

1.2.1 Amplify and Forward Relaying Scheme

To enable cooperation among users, different relay technology can be employed depending on the relative user location, channel conditions, and transceiver complexity. In cooperative diversity networks two main relaying protocols have been studied thoroughly: amplify-and-forward and decode-and-forward Laneman and Wornell (2003). In the amplify-and-forward (AF) scheme the relaying nodes receive the source message, amplify it and then transmit it to the destination node without decoding the message, and thus the relays are called non-regenerative relays This scheme is often used when the relay has limited computing time/power available or the time delay, caused by the relay to decode and encode the message, has to be minimized. In this scheme the source transmits its signal in the broadcasting phase to the destination and the relay, the received signals are given by:

$$y_{s,d} = \sqrt{E_s} h_{s,d} x + \eta_{s,d} \tag{1.1}$$

$$y_{s,r} = \sqrt{E_s} h_{s,r} x + \eta_{s,r} \tag{1.2}$$

where $x, y_{s,d}, y_{s,r}$ denote the transmitted signal and the received signals at the destination and relaying node respectively. $h_{s,d}$ and $h_{s,r}$ are the channel coefficients of the source-destination and source-relay channels, including the effects of shadowing, channel loss and fading. E_s is the average energy transmitted in a single time slot. Assuming all the time slots have unit durations then E_s can be considered as the transmission power. $\eta_{s,d}$ and $\eta_{s,r}$ are additive circularly symmetric white gaussian noise with variances $N_{s,d}$ and $N_{s,r}$ respectively.

In Phase II, the forwarding phase, the relay scales the signal it receives from the source to yield a normalized transmit factor. The relay multiplies the received signal $y_{s,r}$ by the gain G, which is the reciprocal of the normalization factor and is given as:

$$G = \frac{1}{\sqrt{E_s \mid h_{s,r}^2 \mid + N_{s,r}}} \tag{1.3}$$

The signal transmitted from the relay is

$$\begin{aligned} x_r &= G y_{s,r} \\ &= \frac{\sqrt{E_s} h_{s,r} x + \eta_{s,r}}{\sqrt{E_s \mid h_{s,r}^2 \mid + N_{s,r}}} \end{aligned} \tag{1.4}$$

It is clear the gain G depends on the source-relay channel coefficient $h_{s,r}$ and therefore it changes in different transmission intervals. That's why this scheme is referred to as the variable-gain AF relaying scheme.

The signal received at the destination on the relay-destination link can be expressed as:

$$\begin{aligned} y_{r,d} &= \sqrt{E_s} h_{r,d} x_r + \eta_{r,d} \\ &= \sqrt{\frac{E_s E_r}{E_s \mid h_{s,r}^2 \mid + N_{s,r}}} h_{s,r} h_{r,d} x + \sqrt{\frac{E_s}{E_s \mid h_{s,r}^2 \mid + N_{s,r}}} h_{r,d} \eta_{s,r} + \eta_{r,d} \end{aligned} \tag{1.5}$$

At the destination the two signals received on the source-destination link, $y_{s,d}$, and on the relay-destination link, $y_{r,d}$, are combined using any of the different signal combining techniques. We will consider the case where MRC is used at the destination, the combined signal at the destination can thus be given as:

$$y_d = y_{s,d} + y_{r,d} \tag{1.6}$$

and the effective SNR is given as:

$$\gamma = \gamma_{s,d} + \frac{\gamma_{s,r}\gamma r, d}{\gamma_{s,r} + \gamma_{r,d} + 1} \tag{1.7}$$

1.2.2 Decode-and-Forward Relaying Scheme

In the decode-and-forward (DF) scheme, each relay decodes the received information from the source and then generates a new message. The relay then forwards the new message to the destination. That is why this scheme is also called regenerative relaying scheme. In this scheme, in Phase I, broadcasting phase, the source broadcasts a message to the destination and the relays. The relays regenerate the same message and forwards it to the destination in phase II, forwarding phase. The signals received by the destination and a relaying node after phase I are given by

$$y_{s,d} = \sqrt{E_s} h_{s,d} x + \eta_{s,d} \tag{1.8}$$

$$y_{s,r} = \sqrt{E_s} h_{s,r} x + \eta_{s,r} \tag{1.9}$$

The relay then decodes the source signal, the decoding is successful if the transmission rate is less than the capacity of the source-relay link, which is given by

$$C_{s,r} = \log_2(1 + \gamma_{s,r}) \tag{1.10}$$

where $C_{s,r}$ is the capacity in bits per channel use, $\gamma_{s,r}$ is the SNR on the source-relay link. Assuming that the desired average end-to-end rate is R, and since the codeword x is transmitted twice throughout the transmissions process then it must be encoded with rate $2R$. The relay decodes the source message correctly when $2R \leq C_{s,r}$. The relay re-encodes the source message using the same codeword such that $x_r = x$ and retransmits it to the destination in Phase II. The signal received at the destination from the relay, $y_{r,d}$ can be given as

$$y_{r,d} = \sqrt{E_s} h_{r,d} x + \eta_{r,d} \tag{1.11}$$

Assuming a system containing one relay, the destination will then receive two copies of the source message one on the direct link between the source and the destination and the other copy from the relay. At the destination, if no diversity combining is applied then the destination only considers the signal received from the relay, and in that case the rate of the codeword transmitted over both the source-relay and relay-destination links is bounded by the capacity of both links,

$$2R \leq \min\{\log_2(1 + \gamma_{s,r}), \log_2(1 + \gamma_{r,d})\} \tag{1.12}$$

Hence, the average end-to-end achievable rate is given as

$$C = \frac{1}{2} \min\{\log_2(1 + \gamma_{s,r}), \log_2(1 + \gamma_{r,d})\} \tag{1.13}$$

In the case of using diversity combining the two signals received at the destination from the source and the relay can then be combined at the destination using any of the different signal combining techniques. Assuming MRC at the destination, the total received signal at the destination from both links can be given as

$$y_d = y_{s,d} + y_{r,d} \tag{1.14}$$

and the SNR at the output of the MRC is given by

$$\gamma = \gamma_{s,d} + \gamma_{r,d} = \frac{E_s \mid h_{s,d} \mid^2}{\sigma_d^2} + \frac{E_r \mid h_{r,d} \mid^2}{\sigma_d^2} \tag{1.15}$$

The achievable rate in Phase II is given by

$$\log_2(1 + \gamma_{s,d} + \gamma_{r,d}) \tag{1.16}$$

But since the relay must successfully decode the source message in Phase I, the rate transmitted by the source must by less than the capacity of the source-relay link, therefore the maximum achievable end-to-end rate is given by

$$C = \frac{1}{2} \min\{\log_2(1 + \gamma_{s,r}), \log_2(1 + \gamma_{s,r} + \gamma_{r,d})\} \tag{1.17}$$

Outage happens when $R > C$, thus in the first case when no diversity combining is used, the outage probability is given by

$$\begin{aligned} P_{out} &= Pr(\min\{\log_2(1 + \gamma_{s,r}), \log_2(1 + \gamma_{r,d})\} < 2R) \\ &= 1 - Pr(\min\{\log_2(1 + \gamma_{s,r}), \log_2(1 + \gamma_{r,d})\} \geq 2R) \\ &= 1 - Pr(\log_2(1 + \gamma_{s,r}) \geq 2R, \log_2(1 + \gamma_{r,d}) \geq 2R) \end{aligned} \tag{1.18}$$

Considering the Rayleigh fading scenario, where $h_{s,r}$, $h_{r,d}$ and $h_{s,d}$ are independent independent circularly symmetric complex Gaussian random variables, and $\gamma_{s,r}$, $\gamma_{r,d}$ and $\gamma_{s,d}$ are exponentially distributed with mean
$\overline{\gamma}_{s,r} = \mathbf{E}(h_{s,r})E_s/N_0$, $\overline{\gamma}_{r,d} = \mathbf{E}(h_{r,d})E_r/N_0$, and $\overline{\gamma}_{s,d} = \mathbf{E}(h_{s,d})E_s/N_0$,

respectively. Then the outage probability can be given as

$$P_{out} = 1 - Pr(\gamma_{s,r} \geq 2^{2R} - 1)Pr(\gamma_{r,d} \geq 2^{2R} - 1)$$
$$= 1 - \exp(-\frac{2^{2R} - 1}{\overline{\gamma}_{s,r}}) \exp(-\frac{2^{2R} - 1}{\overline{\gamma}_{r,d}}). \tag{1.19}$$

In the case of using diversity combining, MRC in our case, the outage probability of the DF relaying scheme can be given as

$$P_{out} = Pr(\frac{1}{2} \min\{\log_2(1 + \gamma_{s,r}), \log_2(1 + \gamma_{s,d} + \gamma_{r,d})\} < R)$$
$$= Pr(\frac{1}{2} \log_2(1 + \gamma_{s,r}) < R)) + Pr(\frac{1}{2}\{\log_2(1 + \gamma_{s,r}) \geq R))Pr(\frac{1}{2} \log_2(1 + \gamma_{s,d} + \gamma_{r,d}) < R))$$
$$= Pr(\gamma_{s,r} < 2^{2R} - 1) + Pr(\gamma_{s,r} \geq 2^{2R} - 1)Pr(\gamma_{s,d} + \gamma_{r,d} < 2^{2R} - 1)) \tag{1.20}$$

Assuming Rayleigh fading, the outage probability is given as

$$P_{out} = 1 - \exp(-\frac{2^{2R} - 1}{\overline{\gamma}_{s,r}}) + \exp(-\frac{2^{2R} - 1}{\overline{\gamma}_{s,r}})Pr(\gamma_{s,d} + \gamma_{r,d} < 2^{2R} - 1) \tag{1.21}$$

1.2.2.1 Disadvantages of Fixed Relaying Techniques

In relay-based fixed cooperation, the advantages of cooperative diversity come at the expense of the spectral efficiency due to two main reasons:

(i) each relay cannot receive information from the source and transmit to the destination simultaneously in same frequency band (i.e., half-duplex), resulting in two transmission stages from the source to the destination

(ii) the source and relays must transmit on orthogonal channels at either frequency or time domain to avoid interfering with each other Laneman and Wornell (2003) .[1] Techniques like beamforming Narula et al. (1998) , distributed space-time coding (D-STC) Laneman and

[1]In such cooperative networks, with M relaying nodes, the information transmission is performed over $M + 1$ orthogonal channels. This results in system spectral efficiency reduction by $M + 1$.

Wornell (2003), and incremental-relaying Laneman et al. (2004) have been used to alleviate such spectral efficiency deterioration.

1.2.3 Transmit Beamforming with Fixed Relaying Techniques

A cooperative system with multiple relays resembles a distributed antenna array, in such case we can use MISO and MIMO transmission schemes. In general, when using beamforming in systems with a transmitter array of M antennas, the transmissions from those antennas are designed to add coherently at the receiver. Using this technique results in improvement in the SNR by a factor of M, and enhances the mutual information over systems with single-element antennas Narula et al. (1998). The improvements achieved using trasmit beamforming requires the accurate knowledge of the channel to the intended receiver at the transmitter

In cooperative systems with multiple relays, those relays resembles a virtual distributed antenna array. Therefore, with the knowledge of the channel state information (CSI) at the relays, the source and a relay can adjust the phase of their transmissions relying on their knowledge of the channel state information (CSI) so that the two replicas add up at the destination node. This is called distributed transmit beamforming, and can be applied on both AF and DF relaying techniques. In AF relaying, assuming the perfect knowledge of both the source-to-relay and relay-to-destination channels at the relays. In Phase I the source broadcasts its signal to the relays and the destination. The relays normalize the received signal as in regular AF, and then multiplies it with a complex beamforming coefficient. The relays then forward the signal to the destination. With the proper selection of the beamforming coefficient, phase coherent transmission can be achieved. When applying transmit beamforming with DF relaying, the relays decode the source message first and then forward the re-encoded message coherently to the destination. If error-detection is performed at the relays and only relays that had successfully decoded the source message can forward the message to the destination, then the beamforming coefficient takes only the relay-to-destination channel in consideration. If n error-detection techniques are applied at the relays, then the probability of error at the relays must be taken into consideration when choosing the beamforming coefficient. In Sendonaris et al. (2003a) and Sendonaris et al. (2003b), the authors inspired by the results in Narula et al. (1998) presented an information theoretic model for cooperative communication network taking advantage of beamforming. The results of their analysis show that the net effects are higher data rates, at a given power level, as compared to non-cooperative strategy; or if keeping the same data rate as can achieved by the non-cooperative strategy then the required transmit power is reduced and hence increasing the mobile battery life.

1.2.4 Distributed Space-Time Coding (DSTC)

Using transmit beamforming with relaying techniques has shown to enhance the performance of such techniques. But the drawback of using transmit beamforming is that at least channel phase information must be available at the relays which is not always practical. Space-time coding can be used at the transmitter without the knowledge of the CSI. Many authors have examined space-time codes in literature Narula et al. (1999), Tarokh et al. (1998), and Tarokh et al. (1999). In cooperative diversity networks we use a class of space-time coding called distributed space-time coding (DSTC) since the antennas belonging to each relay in the network are located away from eachother. cooperative relaying with DSTC operate in the same manner as the regular fixed repetition cooperative diversity techniques discusses in sections 1.2.1 and 1.2.2, except that the relays will transmit simultaneously on the same subchannel using a designed space-time code, thus enhancing the bandwidth efficiency compared to regular fixed repetition relaying. The use of DSTC in cooperative networks to achieve spatial diversity was first studied in Laneman and Wornell (2003).

Distributed Space-Time Coding (DSTC) can be used with both AF and DF. In AF based cooperative networks, DSTC is applied at the relays to achieve spatial diversity gain without the knowledge of CSI at the relays. Laneman et al. studied DSTC with DF relaying technique in Laneman and Wornell (2003). The authors showed that by using space-time coding a considerable improvement in performance could be reached as all relays can now transmit on the same subchannel during same time slot; although at the expense of higher complexity at the decoder. Both beamforming and space-time coding schemes come with increased transceivers complexity in terms of hardware and time computation and hence increased power consumption.

1.3 Opportunistic Cooperative Relaying

The drawbacks of regular fixed relaying that was stated in section 1.2.2.1, and the increased transceivers complexity accompanied with implementing techniques like transmit beamforming and distributed space-time coding made it required from researchers to find new techniques and protocols to overcome such drawbacks. Opportunistic relaying was introduced through selection relaying and incremental relaying to decrease the complexity and cost of transceivers while improving the spectral efficiency.

1.3.1 Incremental Relaying

In the incremental-relaying strategy Laneman et al. (2004), the relaying process is restricted to pre-specified conditions this results in saving the channels. This is done by using limited feedback from the destination which determines the action to be taken by the relays whether to forward the source's message if the feedback indicates the failure of the transmission on the direct link or to do nothing in the case of the success of the direct transmission.

The idea of the incremental relaying protocols is similar to that of hybrid automatic-repeat-request (ARQ) when viewed in a context involving relaying nodes. In phase I the source broadcasts its signal to the destination and the relay. The source and relay then listens for a feedback from the destination. The destination broadcasts a feedback bit, either ACK, i.e. acknowledge, or NACK, i.e. negative acknowledge, depending on the success or failure of the direct transmission. If the SNR of the source-destination channel is sufficiently high this results in a successful transmission of the source signal on the direct link. The feedback broadcasted from the destination will indicate the success of the transmission and the relay will do nothing. In the case when the source-destination link signal-to-noise ratio (SNR) is not high enough, the feedback broadcasted from the destination requests that the relay re-sends the source signal to the destination. The relay will forward the source signal in phase II to the destination the combines both messages from the direct link and the indirect link using maximum ratio combining (MRC) or any other combining technique (Laneman et al. (2004)).

Incremental relaying can be applied with AF or DF cooperative networks. In incremental amplify-and-forward relaying scheme, in Phase II if the feedback from the destination indicates the failure of the direct transmission,the relay will then amplify the source signal it received in phase I and then send it to destination in Phase II. In incremental decode-and-forward relaying scheme, the relay first detects the source signal and in the case of the failure of the direct transmission it will re-encode it and forwards it to the destination.

The main advantage of incremental-relaying is that it saves the resources of the channel and only uses them when necessary. It was shown in Laneman et al. (2004) and Ikki and Ahmed (2009a) that incremental relaying achieve high spatial diversity and higher achievable rate compared to regular fixed cooperative networks.

1.3.2 Selection Relaying

In the previous sections we studied fixed cooperative relaying schemes in which a relay or multiple relays will forward the source signal to a destination regardless of the channel conditions and whether they successfully decoded the source signal or not in the case of decode-and-forward relaying scheme. We then discussed two techniques that has been used in literature to enhance spectral efficiency; beamforming and distributed space-time coding. Then we discussed the incremental relaying schemes in which the relay is required to forward the source signal only if the destination doesn't receive the source signal correctly on the direct transmission. That's why incremental relaying is considered an opportunistic relaying scheme.

Another opportunistic relaying scheme is selection relaying. In selection relaying a pre-defined criterion is tested at the relaying nodes, and depending on it the relays or a subset of them will forward the source signal. Different criteria to select the relays to forward the source message have been proposed in literature Sreng et al. (2003), Laneman et al. (2004), Jing and Jafarkhani (2009), Bletsas et al. (2005), Bletsas et al. (2007), Selvaraj and Mallik (2011), Zhao et al. (2014), and Beres and Adve (2008). Among the earliest proposed selection schemes are the ones reported in Sreng et al. (2003), Laneman et al. (2004). In Sreng et al. (2003), the authors proposed a nearest relay selection criterion that is based on selecting the relay nearest to the source or to the destination based on either the physical distance or the pathloss. The authors in Sreng et al. (2003) considered their scheme in a cellular network and provided performance analysis in terms of system coverage for a pre-specified SNR under different scenarios of nearest distance and pathloss criteria. The authors in chose the geographic position as their selection criterion. In Laneman et al. (2004), the authors studied a relay selection scheme for DF relay cooperative network where a pre-chosen relay cooperates only if its source-relay channel gain magnitude is above a certain threshold. In this case the relay does not have to participate in the cooperative transmission if its conditions do not meet the selection criterion. Specifically in the selection DF relaying scheme, the source can choose to retransmit its signal to the destination itself if the relay was not able to decode the source signal successfully in Phase I. The source can infer whether the relay successfully decoded its message or not through the knowledge of the CSI on the source-relay link. If the measured $h_{s,r}^2$ is below a certain threshold then the relay doesn't forward the message to the destination, if it is higher than that threshold then the relay will forward the source signal to the destination. The destination combines both signals using MRC. In the case of selection AF relaying scheme, the relay will amplify the source signal before forwarding it to the destination. Outage performance analysis of the proposed scheme Laneman et al.

(2004) was provided assuming Rayleigh channel fading, with relay nodes operating in the half-duplex mode. The authors showed that the selection relaying enables the cooperating nodes to exploit full spatial diversity compared to fixed relaying. For the case of selection DF relaying, the effective SNR at the output of the MRC at the destination is be given by

$$\gamma_{eff} = \begin{cases} 2\gamma_{s,d}, & if \gamma_{s,r} < \gamma_{th} \\ \gamma_{s,d} + \gamma_{r,d}, & if \gamma_{s,r} \geq \gamma_{th} \end{cases}, \tag{1.22}$$

where $\gamma_{th} = 2^{2R} - 1$ and the achievable end-to-end rate of the selection DF scheme is given by

$$C = \begin{cases} \frac{1}{2}\log_2(1 + 2\gamma_{s,d}), & if \gamma_{s,r} < \gamma_{th} \\ \frac{1}{2}\log_2(\gamma_{s,d} + \gamma_{r,d}), & if \gamma_{s,r} \geq \gamma_{th} \end{cases}, \tag{1.23}$$

from which the outage probability can be computed as

$$P_{out} = Pr(\gamma_{s,r} < \gamma_{th})Pr(2\gamma_{s,d} < \gamma_{th}) + Pr(\gamma_{s,r} \geq \gamma_{th})Pr(\gamma_{s,d} + \gamma_{r,d} < \gamma_{th}) \tag{1.24}$$

The authors in Beaulieu and Hu (2006) assumed the DF system model in Laneman et al. (2004), in which a decoding set C, out of M total relays, containing the relays that fully decode the source message based on pre-specified channel conditions, is selected to forward the message to the destination. They derived closed-form expressions for the mutual information outage probability of the system considering MRC combining at the destination. The authors in Beaulieu and Hu (2006) demonstrated that the outage performance doesn't improve with increasing the number of participating relays.

In Selvaraj and Mallik (2011), a scaled-SNR-based selection combining scheme is proposed where a deterministic scale factor (β) is used to incorporate the effect of the source-to-relay link in selecting between the direct link and the indirect link for transmission. The authors derived a closed-form for the end-to-end Symbol error probability (SEP) of this scheme for Binary Phase Shift Keying (BPSK) signaling and studied the relation between the scale factor (β) and SEP and identified an optimum value of (β) at which the SEP is minimum. In Zhao et al. (2014), the authors proposed smart relaying strategies for selection-combining-based decode-and-forward cooperative networks with a network consisting of source, single relay, and destination nodes in which the transmit power of the source and relay node are scaled by specific factors which are optimized at the relay to mitigate the error propagation problem and minimize the BER of the system.

It is clear from the previous analysis that the diversity gain allows the outage probability of the selection DF scheme to remain low even when the channel conditions on the source-relay link deteriorates, which is not the case with fixed DF scheme in which the outage probability increases with the increase in the distance between the source and the relay as the performance is limited by the source-relay conditions in that case. In summary, the selection relaying schemes utilize the CSI of the source-relay link to achieve higher bandwidth efficiency and full diversity order.

1.3.3 Best-Relay Selection Scheme

The best-relay selection scheme was introduced in Bletsas et al. (2005). In this scheme, after the source broadcasts its information to all the relays, the relay with the best instantaneous end-to-end channel conditions is selected to forward the source message to the destination. In DF relaying with best-relay selection, all the relays will try to decode the source's message that was broadcasted by the source in phase I; the broadcasting phase. If they successfully decode the source's message they act as candidate relays for selection. The best relay among the candidate relays in terms of channel conditions is selected to forward the source's message to the destination in phase II; the forwarding phase. The overhead in this scheme is minimal since no feedback is required and no prior knowledge of topology is required in selecting the best relay (Bletsas et al. (2005)).

The authors in Bletsas et al. (2005) proposed a simple signaling method by which the best relay is selected in a distributed manner, in which each relay sets a timer at the beginning of the transmission period. The timer is set to be inversely proportional to a parameter that is based on the instantaneous source to i-th relay, $S - R_i$, and i-th-relay to destination, $R_i - D$, channel gains, say h_i and g_i, respectively. The timer of the relay with the best end-to-end channel conditions will expire first (i.e., reduces to 0). The relay whose timer reduces to 0 first will then be the one that possesses the maximum selection criterion and the one selected to retransmit the source message. That relay broadcasts a short-duration flag packet, signaling its presence as the selected relay. All other relays, while waiting for their timer to reduce to zero (i.e., to expire), are in listening mode. As soon as they hear another relay to flag its presence to forward information (the best relay), they back off. This scheme doesn't require any knowledge of the topology or its estimation. Asymptotic analysis (at high SNR) reported in Bletsas et al. (2005) showed that best-relay selection scheme achieves the same diversity order[2] as cooperative diversity using space-time-coding reported in Laneman and Wornell (2003).

In Bletsas et al. (2007), the authors proposed opportunistic reactive and proactive relaying schemes where the relay selection is performed in distributed manner as well. In the reactive opportunistic relaying, after the source broadcasts its information to the relays, the best relay among the $R_i - D$ links, in terms of instantaneous signal strength, is chosen from a decoding set to retransmit the source message to the destination. In the proactive opportunistic relaying the best relay is selected, before the source transmits its message, in a distributed manner based on the instantaneous signal strength on both $S - R_i$ and $R_i - D$ links. While the selected relay broadcasts a flag packet notifying the rest of the network about its availability, the other relays will enter an idle mode even during the source transmission afterward. At this point, the source will transmits its message only to that selected relay. This way of relay selection in the proactive strategy makes it energy-

[2]Diversity order is defined as the number of independent channels available through which replicas of the same information signal can be transmitted simultaneously (Zheng and Tse (2003), (Proakis et al., 1994, pp. 689-692).

efficient scheme since all relays except the best relay can enter an idle mode during both phases of cooperative transmission; i.e. broadcasting and forwarding phases. However, at the expense of extra CSI computation. The authors in Bletsas et al. (2007) showed that both reactive and proactive opportunistic relaying selection strategies give same outage behavior as the decode-and-forward strategy where all potential relays participate in the cooperation process.

In Beres and Adve (2008) the authors derive an approximation to the outage probability of the best-relay selection at high SNRs for the case when only the best relay among the decoding set C will forward the source message to the destination. In ikki2009exact, the authors considered the decode-and-forward cooperative diversity with best-relay selection scheme, proposed in Bletsas et al. (2005), over independent non-identical Rayleigh fading channels and derived an exact closed-form expression for the probability density function (PDF) of the total SNR at the destination assuming MRC combining. Using that expression the authors derived exact closed-form expressions for the error probability and average channel capacity. In ikki2010performance, the authors extended their previous analysis in ikki2009exact and using that expression that they had derived for the PDF of the total SNR at the destination they derived an exact closed-form expression for the outage probability for the model under consideration that are valid for all SNR regions. In ikki2010performance2, the authors proposed a modified version of the best-relay selection scheme. In best-relay selection scheme, only the best relay forwards the source signal to the destination. But the selected best relay might be unavailable, in this cause the proposed scheme by the authors will choose the second best relay. If the second best relay is also unavailable then the third relay is selected or generally the N^{th} best relay among the decoding set C is selected to forward the source signal. The authors derive the closed-form expression for the probability density function (PDF) of the SNR of the signal received at the destination from the relay. Then the authors use the moment generating function (MGF) to derive the closed-form expression of the PDF of the SNR of the total received signal at the destination coming on both the direct and the indirect links. The authors use the PDF of the SNR to derive the symbol error probability, outage performance, and asymptotic error probability of the system. The best-relay selection scheme can be considered as a special case of this scheme when $N = 1$.

In Hwang et al. (2009) the authors proposed a new scheme that incorporates the best-relay selection strategy with the incremental relaying. In this scheme the best relay among M relays is selected to retransmit the source message to the destination only in the case when the feedback sent from the destination to the source indicates the failure of transmission on the direct link. In such a case, when the direct link fails, the two signals received at the destination are then combined using MRC. The authors consider the case of amplify-and-forward transmission and they analyze the performance of the systems in terms of the average spectral efficiency, the average BER, and the outage probability showing improvements in the spectral efficiency and outage probability and satisfying the required BER performance in the same time. In Ikki and Ahmed (2011), the authors derive closed-form expressions for the bit error rate, outage probability and average channel capacity for the best-relay selection scheme with the incremental relaying in both amplify-and-forward and decode-and-forward transmissions.

The best-relay selection scheme is an ideal protocol that achieves better performance compared to conventional cooperative communications, but in practice the best relay might not be available due to many reasons including: scheduling, load balancing, in this case, the second best relay or more generally the N^{th} best relay might be selected. The study of the N^{th} best-relay is also need in evaluating the loss in performance due to an error in selecting the best relay that can be cause by imperfect channel state information (CSI) feedback or in the case of outdated channel information (OCI) where the relay that was the best relay at the time of selection was not the best at the transmission time instantSalhab and Zummo (2015). It is obvious that the best-relay selection scheme is a special case of the N^{th} best-relay selection scheme. The N^{th} best selection scheme in cooperative diversity networks without spectrum sharing was studied in Ikki and Ahmed (2009b,c); Lateef et al. (2010); Ikki and Ahmed (2010a); Chu (2011); Ko and Woo (2012). The performance of conventional AF and DF relay networks with the Nth best relay selection over Rayleigh fading channels was studied in Ikki and Ahmed (2009b, 2010a). The authors in Lateef et al. (2010) derived closed-form expressions for the symbol error rate of AF systems with N^{th} best-relay selection over independent and nonidentically distributed (inid) Rayleigh fading channels, while the authors in Ko and Woo (2012) derived an approximate expression for the outage probability of an AF system with N^{th} best-relay selection scheme for independent and nonidentically distributed (inid) Rayleigh fading channels . The authors in Chu (2011) derived the asymptotic symbol error rate for a conventional AF relay network with the Nth best relay selection over Nakagami-m fading channels.

CHAPTER 2

Cognitive Radio Networks

The increasing demand for high-data rate wireless transmission creates a challenge of utilizing the radio spectrum in an efficient way. The inefficient use of the radio spectrum today arises from the problem of white-space spectrum where a lot of the spectrum assigned is underutilized. One possible solution is the use of dynamic spectrum access (DSA). Cognitive radio (CR) is an enabling technology for DSA that provides unlicensed users, called secondary users (SUs), with the capability of sharing the licensed spectrum with licensed users, called primary users (PUs), in an opportunistic manner Mitola and Maguire (1999); Haykin (2005).

2.1 Cognitive Radio Schemes

There are three schemes of cognitive radio networks depending on how the secondary users use the spectrum. These schemes are the interweave, overlay, and underlay schemes.

2.1.1 Interweave Scheme

In the interweave mode, the secondary users are allowed to use the spectrum without causing any interference to the primary network following an interference avoidance strategy. Therefore, secondary users monitors the spectrum periodically to detect a vacant space in the spectrum, known as a spectrum hole, that it is not utilized by the primary user and efficiently utilizes it to transmit its own data. Since the transmit power of the SUs is not bounded by an interference constraint, interweave spectrum access can better system performance in terms of outage probability and error probability as compared to underlay and overlay networks at the same propagation conditions. Another reason is that the received signal doesn't suffer from interference from the primary network. However, there are challenges to implementing the interweave scheme. Detecting the spectrum holes requires sensing the activity of the primary network in several radio channels, this becomes more difficult if the primary users are dynamic causing their spectral activity to change quickly and the secondary users are then required to switch on and off, and switch frequency channels very quickly. Also, increasing the range of the secondary network reduces the correlation between the spectrum sensed at the transmitter and at the receiver of the secondary network due to different signal strengths of the primary signal at the transmitter and the receiver.

2.1.2 Underlay Scheme

In the underlay mode, the secondary and the primary users share the frequency spectrum under the condition that the interference induced by the secondary transmission at the primary users is below a predefined threshold. This is done by restricting the transmit power of the secondary users which leads to increasing the effectiveness of spectrum utilization at the cost of reducing the radio coverage in the secondary network. The challenge in implementing the underlay scheme is not tracking the primary activity and adapting its transmission accordingly but ensuring that the secondary transceivers are capable of operating at low SNR.

2.1.3 Overlay Scheme

In the overlay mode, the secondary user cooperates with the primary user by relaying the primary user data in exchange for using the licensed spectrum. This requires the secondary users to have knowledge about the primary network beyond spectrum occupancy such as code books. The primary network may have higher acceptance to the secondary network since it is contributing to improving its performance. The overlay scheme can be seen as an evolution of the underlay scheme where the maximum allowable interference threshold is increased resulting in better performance for the secondary network. Although the overlay scheme offers advantage over the underlay scheme but this scheme requires a high degree of complexity in the secondary transceivers, and assumes that the secondary transceivers know the channel state information to guarantee that the primary signal is successfully decoded. Also, a power control mechanism is needed to determine how much power should the secondary transmitters devote to the primary and the secondary signals.

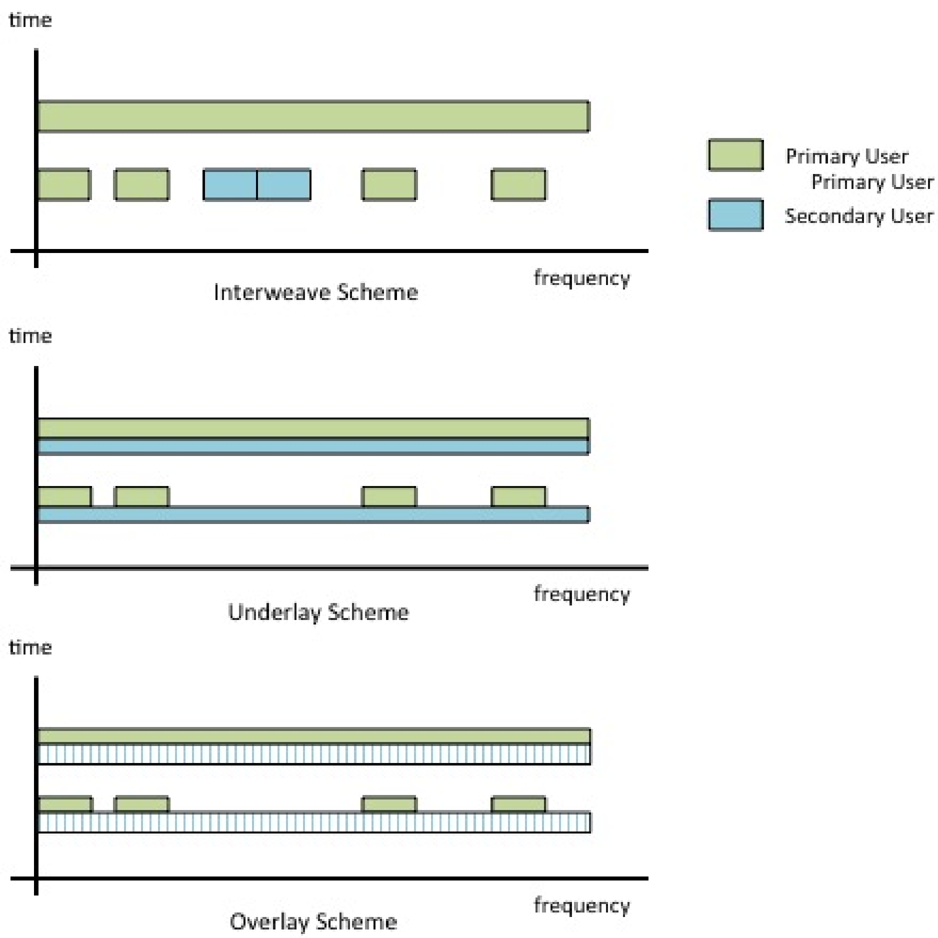

Figure 2.1. Different Schemes of Cognitive Relay Network

In my dissertation, I consider the underlay mode, where the secondary users have to adapt their transmission powers to keep the interference level at the primary user below a predefined thresholdGoldsmith et al. (2009).

2.2 Cooperation in Cognitive Radio Networks

Cooperation relaying has been proposed to enhance the performance of cognitive radio networks. Cooperation between secondary users can increase the coverage of the secondary, maximize throughput and received signal to noise-interference ratio (SINR). Cooperation between primary and secondary users can help improve the performance of both networks. Cooperation can be done using amplify-and-forward or decode-and-forward techniques that were discussed in chapter 1.

In underlay Cognitive radio networks the secondary transmitters have to adapt their transmission power so that the interference incurred at the primary user is below a maximum allowable interference threshold, this constraint on the transmission power degrades the performance of the secondary network deployed in fading environments Lee et al. (2011), Zou et al. (2010), Guo et al. (2010), Ding et al. (2011), Si et al. (2011), Duong et al. (2011), Hussain et al. (2012), Yan et al. (2011), Duong et al. (2012), Xu et al. (2012), Chamkhia et al. (2012), Chen et al. (2012), Si et al. (2012), Yang et al. (2014). Therefore, relaying techniques are incorporated in underlay cognitive networks to increase the area of coverage of secondary users.The authors in Ganesan and Li (2007) studied using cooperative diversity to spectrum sensing, and they showed that the performance of sensing is improved by using user cooperation. In Kim et al. (2008), the authors compared the performance of cognitive relay networks to that of conventional relay networks. The authors of Han et al. (2009) showed that forwarding the primary signal by a secondary relay node improves the primary outage probability and in return the SUs get more opportunities to access the unoccupied frequency bands. In Lee et al. (2011), the authors evaluated the outage probability of a cognitive relay network where the relay is selected among a set of relays based on the max-min criterion, and in the absence of a direct link between the source and the destination. The authors showed that the outage probability of cognitive relay networks can be divided into two parts; the outage probability of the conventional relay network and an increase in outage probability resulting from the interference constraint. They also showed that the outgae probability is affected by the ratio of the distance between the secondary transmitter and the primary receiver to the distance between the secondary transmitter and the secondary receiver. The best relay was selected from a set of relays that were capable of decoding the source message in Guo et al. (2010). The authors also showed that increasing the allowable interference at PUs results in better cooperative diversity of the secondary system.

In Zou et al. (2010); Si et al. (2011) the secondary user's transmission is constrained by the outage probability at the primary receiver. In Zou et al. (2010) the relay selection scheme is based on the statistics of the second hop to select the best relay while taking into consideration the mutual interference between PU and SU, with a constraint of satisfying a certain required outage probability at the PU. In Si et al. (2011) the number of the participating relays in the relaying is determined by the partial channel state information (CSI) between the relays and the primary receiver so that the outage probability at the primary receiver is kept below a predetermined value. The authors in Ding et al. (2011) derived an asymptotic expression for the outage probability of several relay selection schemes, i.e. selective AF, selective DF, and AF with partial relay selection; ignoring the direct link between the source and the destination. Yan et al. in Yan et al. (2011) derived the exact outage probability for a cognitive DF relay network where a maximum power constraint was considered. The outage performance and error probability of three different relay selection schemes for DF CRNs were studied inChamkhia et al. (2012) where the selection criteria proposed were selecting the relay with maximum SNR on the second hop, the relay with the minimum SNR on the second hop and finally the relay that causes minimum interference to the primary network. They find that the first selection scheme enhances the system performance, although the second scheme provided less system performance but it is a good power saving solution, and finally, the third scheme gave an acceptable level of performance for the secondary network while keeping the interference to the primary user at a lower level.

In Sagong et al. (2011), the authors evaluated the capacity for reactive decode-and-forward (DF) scheme in cognitive relay networks over Rayleigh fading channels. The authors in Jaafar et al. (2011) proposed a cooperative scheme for cognitive networks where a secondary relay node assists the primary and the secondary transmissions simultaneously. They proved that for some relays positions, the secondary outage performance can be improved significantly while respecting a threshold on the primary outage probability. However, this improvement comes at the cost of an increased transmit power at the relay node.

The authors in Xu et al. (2012) studied a cognitive DF relay network with a single relay taking into consideration the effect of the interference from the primary transmitter on the secondary receiver. The interference from PU transmitter results in the received interference plus noise ratios (SINRs) at the SU destination being correlated. Building on that work, the authors in Si et al. (2012) extended the study to an underlay cognitive relay system with multiple relays showing that although the PU interference degrades the SU's performance but this can be alleviated by increasing the number of relays. In Jaafar et al. (2012b), the authors proposed an adaptive cooperative scheme where the relay node is able to choose independently when to cooperate and which transmissions to assist, depending on the channel condition that links it to the primary and the secondary nodes.

Cognitive radio networks employing amplify-and-forward relaying were studied in Ding et al. (2011); Duong et al. (2011); Hussain et al. (2012); Duong et al. (2012); Chen et al. (2012). The authors in Duong et al. (2011) studied a cognitive AF relay network over non-identical Rayleigh fading channels for a single relay, while in Hussain et al. (2012) the outage and error rate performances of an underlay fixed-gain amplify-and-forward CRN were derived for a reactive relay selection scheme where the relay with that maximizes the SNR on the relay-destination link is selected to forward the secondary source message. The authors in Duong et al. (2012) derived a lower bound expression for the secondary outage probability of a cognitive AF relay network with a single relay over Nakagami-m fading channels. The outage performance of AF CRN with multiple primary users was studied in Chen et al.

(2012).

In Yang et al. (2014) the authors studied opportunistic DF relaying where only the best relay is selected to forward the secondary source message, they derived upper and lower bound expressions of the outage probability taking into consideration the effect of the PU interference on the secondary network. Cognitive relay networks employing the N^{th} best-relay selection scheme were studied in Zhang et al. (2013); Duy and Kong (2013); Zhang et al. (2015); Salhab and Zummo (2015). In Zhang et al. (2013), the authors investigated the outage performance for a cognitive decode-and-forward relay network with N^{th} best-relay selection scheme over i.i.d. Rayleigh fading channels, their results showed that both the relay selection scheme and the number of relays greatly impact on the outage performance of the system. The study was later extended to cognitive relay networks over Nakagami-m fading channels in Zhang et al. (2015). While cognitive amplify-and-forward relay networks with N^{th} best-relay selection was studied in Duy and Kong (2013) without taking into consideration a maximum power limit at the secondary transmitter.

Conventional relaying schemes make an inefficient use of the degrees of freedom because of the fixed 2-phase transmissions. Indeed, it is possible that the destination succeeds to decode the transmitted signal using only the received signal on the direct link at the first phase. Hence, the second transmission becomes unnecessary and resource wasting. As a solution, incremental relaying can be seen as an extension to hybrid Automatic- Repeat-Request (ARQ), where a selected relay node will repeat the source's signal when a negative feedback is sent by the destination at the end of the first phase. Considering the improvement in spectral efficiency that can be offered from using incremental opportunistic relaying, the performance of cognitive relay networks implementing incremental relaying has been studied in literature Liu et al. (2011) , Bao and Bac (2011), Bao et al. (2011), Jaafar et al. (2012a), Tourki et al. (2013), Tourki et al. (2014), Huang et al. (2013), Chu (2014), Majhi and Banerjee (2015). In Liu et al. (2011), the authors analyzed the throughput of a cognitive incremental relaying network that employed distributed zero-forcing beamformer. In Bao and Bac (2011), the authors study the outage performance of cognitive incremental decode-and-forward relaying with a single relay over Rayleigh fading channels. The authors extended their study in Bao et al. (2011) to multiple relays from which the best relay is selected to forward the source message if the source-destination direct link falls below a certain threshold. In Jaafar et al. (2012a), the authors proposed an incremental relaying protocol in which a secondary relay is selected to assist the primary transmission and another secondary relay is selected to assist the secondary transmission depending on the conditions of the direct link between the primary source and primary receiver and the direct link between the secondary source and secondary destination respectively. The authors in Tourki et al. (2013) derived a closed-form expression for the outage probability of a CRN using incremental DF relaying proposing two schemes depending on the channel state information (CSI) at the secondary source. The authors extended their work in Tourki et al. (2014) studying the effect of outdated CSI on incremental opportunistic relay selection underlay cognitive networks. In Huang et al. (2013), the authors studied the outage gap between decode-and-forward relaying and incremental decode-and-forward relaying in cognitive radio networks taking into consideration the mutual interference between the PU and the SU. The authors in Chu (2014) studied the outage probability and diiversity-multiplexing tradeoff of incremental decode-and-forward relaying and incremental amplify-and-forward relaying over Nakagami-m channels. In Majhi and Banerjee (2015), the authors derived an asymptotic expression for the outage probability of incremental decode-and-forward relaying in an underlay cognitive network with multiple primary users.

CHAPTER 3

Internet of Things Systems

The tremendous growth of different communication industries during the last decades has developed new technologies to access real time information for different applications. Internet of Things (IoT) is the theme that provides ubiquitous connections anytime to everything through different means such as radio-frequency identification tags, wireless sensor networks, actuators, cellular phones, motor vehicles, surveillance cameras, etc. Therefore, IoT aims to provide smart network connections allowing not only the traditional human-to-human communications but also human-to-machine communications and machine-to-machine (M2M) communications. These different smart communication links can foster the development of many applications that use enormous amount of data generated by objects to support new services in different fields Atzori et al. (2010), Stankovic (2014), Al-Fuqaha et al. (2015).

3.1 Machine-to-Machine (M2M) Communications

M2M communications are intelligent type of communications where the data generation, exchange, and processing between machines are done without or with low human interventions Whitehead (2004). An M2M network is formed mainly of a large number of low cost machines with different functions offering diverse services. Therefore, M2M communication can be seen as a practical realization of IoT networks such as home automation, traffic management, health care, environment monitoring, smart grids, public safety applications, etc Whitehead (2004); Niyato et al. (2011); Zhang et al. (2012); Aijaz and Aghvami (2015).

The IoT smart objects are expected to reach 212 billion entities deployed globally by the end of 2020 Gantz and Reinsel (2012). By 2022, M2M traffic flows are expected to constitute up to 45% of the whole Internet traffic Evans (2011) and Gantz and Reinsel (2012). Beyond these predictions, McKinsey Global Institute reported that the number of connected machines (units) has grown 300% over the last 5 years Choudhary and Jain (2016). Traffic monitoring of a cellular network in the U.S. also showed an increase of 250% for M2M traffic volume in 2011 Shafiq et al. (2012).

3.2 Cognitive M2M (CM2M) Networks

The implementation of huge numbers of sensors with different traffic requirements creates several challenges such as accessing the spectrum, communicating easily with other machines and meeting the increased energy requirement. The spectrum resources become scarce with the proliferation of wireless devices that support very high data rate services. Therefore, spectrum access technology can be adopted to utilize the spectrum more efficiently with controlled interference techniques to reduce the impact on authorized users. Cognitive M2M (CM2M) has been proposed very recently to enhance the efficiency and reliability of M2M communications Zhang et al. (2012); Aijaz and Aghvami (2015).

In a CM2M, there are usually two systems utilizing the same frequency range: the primary and secondary systems Mitola and Maguire (1999); Haykin (2005). The primary system refers to the system that has the unlimited access to the licensed spectrum Nekovee (2010). While the secondary system dynamically access the same spectrum using one of the well-known spectrum sharing paradigms; interweave, overlay, and underlay modes to limit and control its interference on the primary system. Thus, CM2M can improve the spectrum utilization by giving different machines the opportunity to exploit under-utilized spectrum bands while meeting the energy and service quality requirements Zhang et al. (2012); Aijaz and Aghvami (2015). In Zhang et al. (2012) Zhang, et. al introduced the cognitive dimension to M2M to enhance the performance of conventional M2M commuincations. They discussed the motivations to use CM2M communications and the applications of the new paradigm in different fields. In Aijaz and Aghvami (2015), the authors investigated CM2M communications from a protocol stack perspective, the challenges, standardization efforts, and the latest developments in the Physical, MAC, and Transport layers. The research in CM2M communications still needs continuous improvement in spectrum access, coverage extensions and efficient energy utilization.

3.3 Why Use Cognitive Radio in M2M

There are many motivations to using cognitive radio in M2M networks, some of these motivations come from the technical challenges that CM2M can solve and from the opportunities it can create and the performance and functionality of applications that can be enhanced by deploying CM2M.

3.3.1 Technical Challenges Solved by Applying Cognitive Radio to M2M Communications

Cognitive M2M (CM2M) communications successfully solve many of the challenges facing M2M networks, some of these challenges are described below

- *Spectrum scarcity*:

  The increasing number of connected M2M devices is a major challenge to IoT and M2M communications. As we mentioned before the number of connected devices will rise tremendously in the very near future (e.g. according to Gantz and Reinsel (2012), 212 billion entities will be connected by the end of 2020). This will create a major challenge for existing communication networks that will suffer from spectrum congestion. The dynamic spectrum access capabilities of cognitive radio networks can allow us to utilize the existing spectrum more efficiently to accommodate large-scale data transmission.

- *Interference*:

  The huge number of connected devices will create another challenge in terms of significant interference issues between self-existing and co-existing M2M networks. This interference may seriously degrade the performance of not only M2M communications but also the conventional human-to-human (H2H) services that operate in unlicensed band such as the industrial, scientific and medical (ISM) band (worldwide unlicensed band of 2.42.485 GHz). Therefore, there is a need to explore alternative spectrum opportunities such as utilizing the TV white space (TVWSs). TVWSs are large portions of the UHF/VHF spectrum that is now available on geographical basis due to the switchover from analog to digital TV Nekovee (2009). TVWSs are attractive because they provide significant bandwidth and superior propagation characteristics. This propagation characteristics provide wide area coverage and better penetration into buildings. This is specifically attractive in applications where devices are spread over a large area and in areas where wireless propagation if difficult, an example for that is smart meters in a smart grid deployed in garages, under stairs, or in metallic cages.

- *Coverage issues*:

  In some M2M applications such as smart grid, the devices' locations are hugely variable. Some of these devices may be employed in areas where wireless propagation is not always guaranteed, especially if these devices operate in the industrial, scientific and medical (ISM) band (worldwide unlicensed band of 2.42.485 GHz). Through dynamic spectrum access, cognitive radio-equipped M2M networks can effectively overcome this issue by accessing better propagation bands such as TV white spaces (TVWS).

- *Green requirement*:

  Machines in M2M networks are mostly low-cost and low-power devices deigned to operate for several years without battery replacement, hence energy efficiency is a fundamental requirement in M2M communication and energy saving is extremely important to prolong the network lifetime. Cognitive radio technology has been demonstrated to be green (or energy efficient), as the devices in a secondary network can adaptively adjust their transmission power levels based on operating environments without interfering with the primary network Palicot (2009). Such intrinsic context-aware and adaptable functionality make cognitive radio a key enabler for the future generations environment-friendly radio systems.

- *Machine heterogeneity*:

  An M2M network comprises a large number of machines that are divers in terms of applications and service, this may cause diversity in network protocols and data formats. The cognitive ability is particularly suitable for M2M communication to deal with device and protocol heterogeneity. The capability of devices to be smart enough to communicate with other devices freely makes M2M networks more efficient and flexible.

3.3.2 Applications of CM2M Communications

The combination of cognitive radio and M2M communications will benefit many applications with the added functionality and better performance as well as introducing new applications such as home multimedia distribution systems, intelligent roads for future intelligent transportation systems (ITSs), and urban broadband services.

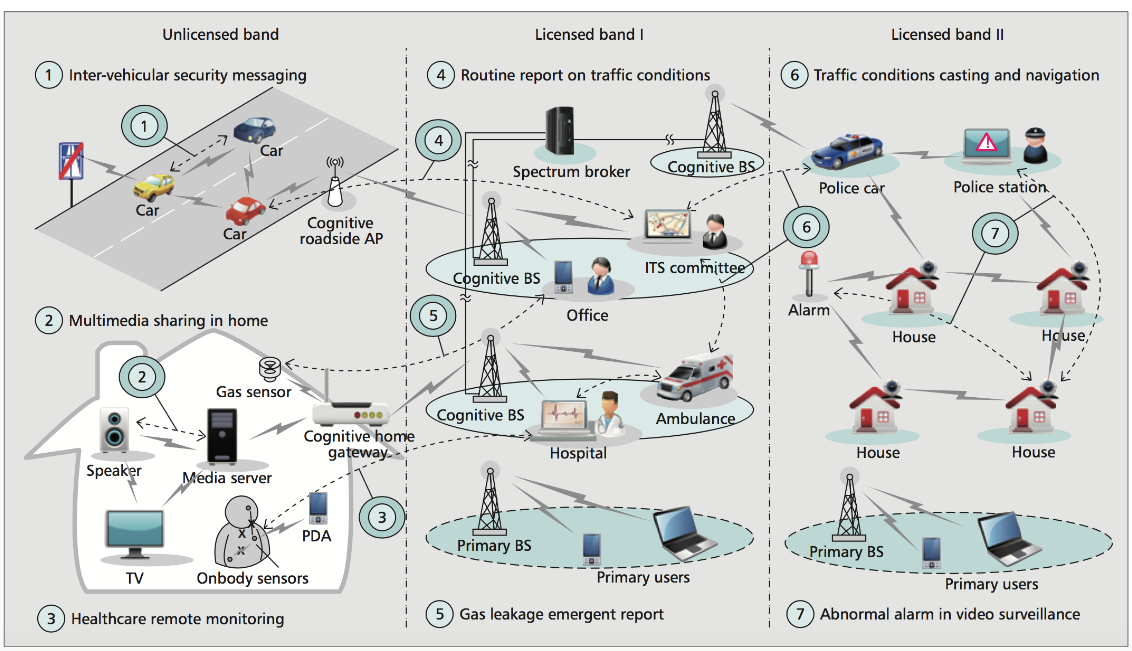

Figure 3.1. Some of CM2M communications applications [Zhang et al. (2012)].

- Home Multimedia Distribution and Sharing

  Home networks are growing rapidly with the devices and machines composing those networks being highly diverse including cellular phone, personal computers, smart TVs, and other electronic devices. M2M communications will become a dominant communication paradigm in home networks with the increasing penetration of embedded devices. Multimedia distribution and sharing is a main application of home M2M networks. The challenge facing this service is the radio resources, as home networks traditionally use the ISM band which is becoming over-crowded. The inherent advantages of cognitive radio which enables dynamic access to additional spectrum, e.g., in TVWSs, make CM2M for multimedia distribution and sharing very encouraging.

- Smart Power Grid

  M2M Communications enable networked smart meters and advanced metering infrastructure in the smart grid Farhangi (2010). The amount of energy-related data generated in the near future is estimated to rise up to tens of thousands of terabytes proposing a significant challenge for any existing communication network. The usage of cognitive radio in the smart grid potentially improves spectrum utilization and communication capacities to support large scale data transmissions. CM2M can help save energy consumption in smart meters that has relatively low data volumes enabling greener power grids. Wind farm area networks are normally deployed in remote areas, where there are plenty of TV white spaces. CM2M over TV white spaces becomes an ideal choice in this scenario.

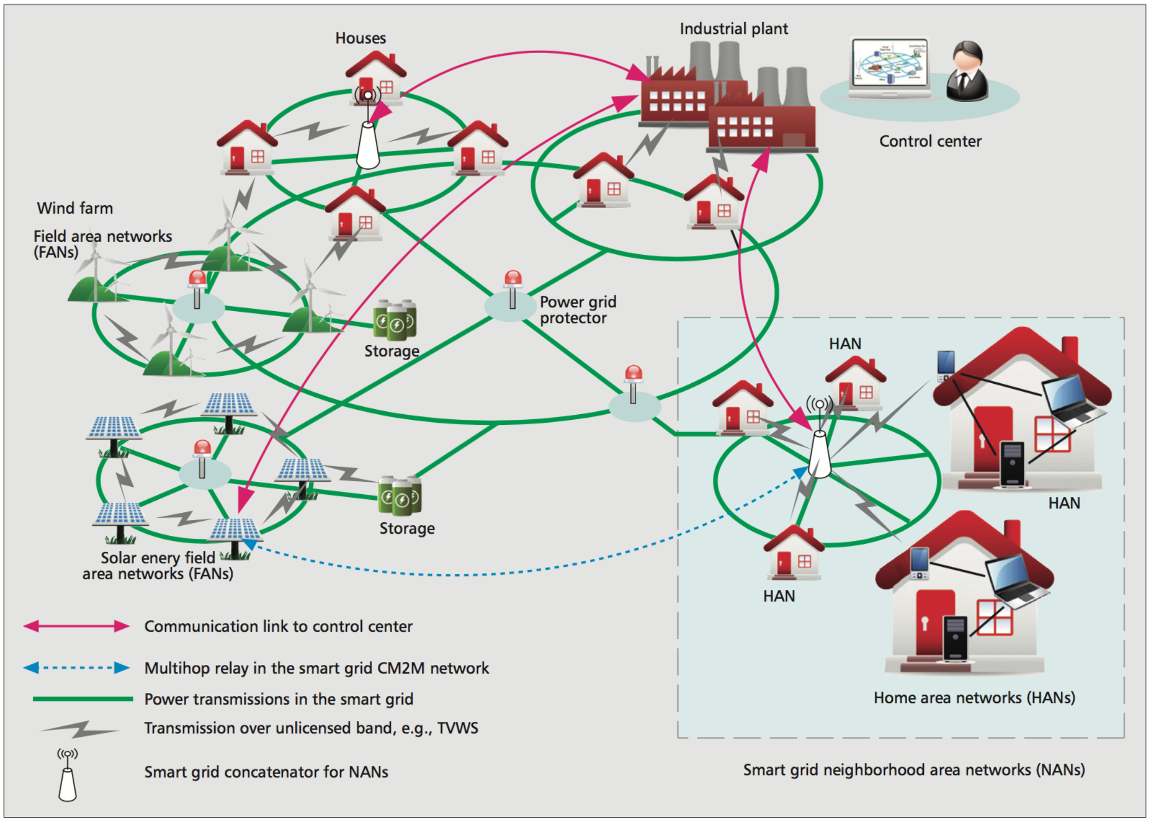

Figure 3.2. CM2M for the smart grid [Zhang et al. (2012)].

- Intelligent Transportation Systems

  The future Intelligent Transportation Systems (ITS) is envisioned to automatically and seamlessly interconnect all objects, where M2M will play an important role in connecting cars, busses, traffic lights, trams, roads with embedded sensors, and emergency crews. The Dedicated Short Range Communications (DSRC) band has been allocated in the USA at 5.9 GHz for Vehicle-to- Roadside (V2R) and Vehicle-to-Vehicle (V2V) communications, which are two typical M2M communications scenarios in ITS. However, only a part of this spectrum band is available in Europe. In addition, the DSRC spectrum is envisioned to become increasingly congested, in particular when the density of the vehicles increases. For V2V and V2R communications, dynamic spectrum sharing between DSRC radios and the roadside access points can potentially improve the communication efficiency as well as the spectrum utilization. Intelligent roads are another innovation in using CM2M in ITS. The future intelligent road is cognitive in the sense that it can listen, sense, think, and act. Such cognition capability is enabled by intelligent sensors on the road surface, information processing, and communications devices on the road, which makes all roads interconnected. This will make all players in the transport sectors intelligent and interconnected improving road traffic efficiency and safety.

- eHealthcare

  In a typical patient remote monitoring application, a patient is staying at home with medical sensors connected to his body that continuously monitor his body conditions and transmit the collected data to a medical instrument. Meanwhile, the collected data is also transmitted to a gateway, which is connected to a hospital server through the Internet. The doctor in the hospital can remotely monitor the patient's health condition on a real-time basis. To ensure the persistent pervasive monitoring, sensor nodes should operate in a low-power mode to prolong the lifetime of the sensors. To fulfill end-to-end transmissions, eHealthcare applications usually involve interconnection of hybrid networks and they may transmit heterogeneous traffics in a green manner. In addition, body area networks could be extended to transmit voice and pictures or video of body areas. It is envisioned that CM2M will be very important to tackle scarce radio resources, network heterogeneity, and green issues.

3.4 Architecture and Domains of CM2M Networks

3.4.1 CM2M Network Architecture

The CM2M network is composed of a primary network and the M2M secondary network. Cognitive machines in a CM2M network coexist with the primary users and utilize the spectrum in an opportunistic manner.

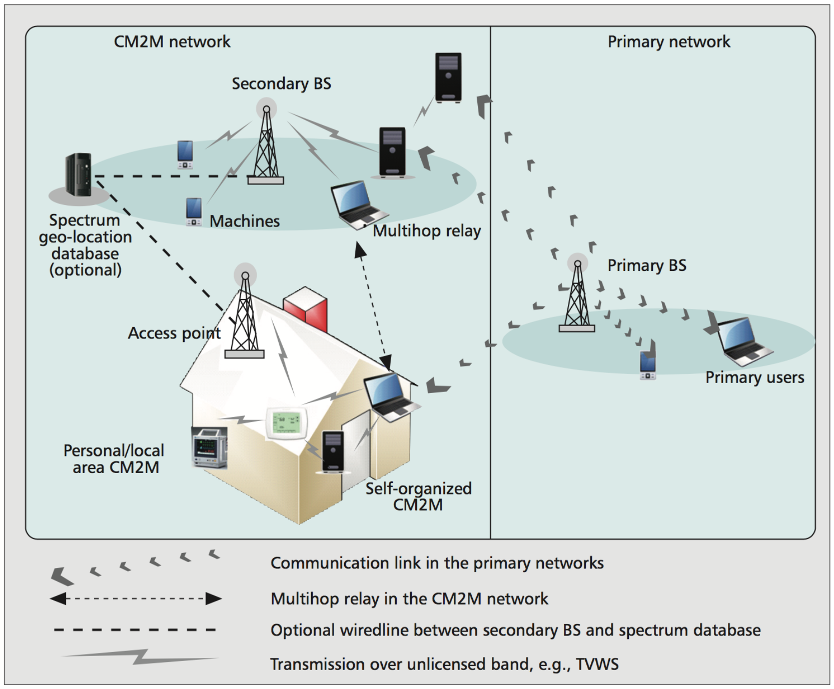

Figure 3.3. CM2M network architecture [Zhang et al. (2012)].

Primary Network: This refers to the wireless network that is licenses to use the spectrum. Typical primary users are mobile terminals in cellular networks (e.g., 2G/3G/LTE) or TVs in TV broadcasting networks. The primary users in a primary network have the exclusive right to access the licensed spectrum but can possibly coexist with a CM2M network under the constraint of not affecting primary transmissions.

CM2M Secondary network: This is the CM2M network looking to use the spectrum licensed to the primary network in an opportunistic manner. The secondary CM2M networks contains machines that are performing information generation, processing and actuation for sensing and/or controlling the physical world and they are cognitive in the manner they communicate with others and sense the spectrum that they are trying to access. In a centralized CM2M network, a secondary base station manages the that machines that are communicating within its coverage and acts as an information entrance to external networks. All secondary base stations communicates with an option spectrum broker that is responsible for coordination spectrum allocation among multiple CM2M networks.

3.4.2 CM2M Communication Domain

CM2M operate in different frequency bands, these bands can either be licensed to specific user or unlicensed. Cognitive M2M networks operating in unlicensed frequency bands where there is no primary network assigned this band can perform power control or spectrum handoff to coordinate with other coexisting cognitive machines. In the case of operating in licensed frequency bands, CM2M networks have two network structures, infrastructure-based and ad-hoc settings. In an infrastructure-based access topology, the network is organized in a centralized manner. A cognitive network infrastructure including the secondary BS and the spectrum database exists. In an ad hoc topology, machines are autonomously organized to constitute a multihop network for information delivery. CM2M communications across multiple bands could be viewed as the combination of several cases that use M2M communications in a single band.

3.4.3 Coexistence of CM2M Systems

Several CM2M networks can co-exist in the same geo-location. In a home area, for example, there can be a CM2M network for home multimedia distribution and sharing, and another for the networked smart meters. The issue of co-existence is more complicated in TVWS compared to the case of license-exempt access to, e.g., the ISM band, this is due to the following reasons:

- The TVWS spectrum is expected to be shared by several access technologies such as 802.11ah, 802.11af, LTe, and the existing and new standards for M2M communications. There is a huge heterogeneity between these technologies as use different transmission power levels, network architecture, and terminal capabilities incurring technological challenges.

- ISM bands don't incur such technological challenges because regulators have imposed low EIRP limits (100 mW in Europe, up to 1W in USA) to make efficient spatial sharing possible. It is difficult to impose an EIRP threshold in TVWS because of the mix of high and low-power use.

One of the main challenges is how to ensure fair sharing in TVWS between these heterogeneous users. One potential short-term solution is to use an additional layer in geo-location databases that manage sharing between heterogeneous systems. This should be possible because the geo-location databases have access to information on location and type of devices. However, this is based on the assumption that all devices need to report back to the geo-location databases provider their position, the frequency and the transmission power they are using. Furthermore, for sensing-only devices, this solution may not be feasible. Another possible approach is that the heterogeneity should be considered as a benefit instead of a disadvantage in efficiently accessing and sharing of the spectrum. Packet scheduling mechanisms may also be deliberately designed based on local interference conditions.

CHAPTER 4

Generalized Cooperative Spectrum Sharing Scheme for Internet of Things Systems

A generalized cooperative spectrum sharing (GCSS) scheme for machine-to-machine (M2M) communications is proposed in internet-of-things (IoT) systems. The proposed scheme makes use of the existence of massive connected machines to overcome the challenges of spectrum scarcity while avoiding interference and meeting the green requirements of IoT systems. The cooperative proposed scheme extends the coverage of M2M wireless network as well as increasing the throughput while reducing the energy consumption of the connected low power devices. The performance of the GCSS scheme is evaluated analytically by the outage performance by deriving the outage probability. Furthermore, a numerical simulations are presented to support the theoretical findings.

4.1 Introduction

The tremendous growth of different communication industries during the last decades has developed new technologies to access real time information for different applications. Internet of Things (IoT) is the theme that provides ubiquitous connections anytime to everything through different means such as radio-frequency identification tags, wireless sensor networks, actuators, cellular phones, motor vehicles, surveillance cameras, etc. Therefore, IoT aims to provide smart network connections allowing not only the traditional human-to-human communications but also human-to-machine communications and machine-to-machine (M2M) communications. These different smart communication links can foster the development of many applications that use enormous amount of data generated by objects to support new services in different fields Atzori et al. (2010); Stankovic (2014); Al-Fuqaha et al. (2015).

M2M communications are intelligent type of communications where the data generation, exchange, and processing between machines are done without or with low human interventions Whitehead (2004). An M2M network is formed mainly of a large number of low cost machines with different functions offering diverse services. Therefore, M2M communication can be seen as a practical realization of IoT networks such as home automation, traffic management, health care, environment monitoring, smart grids, public safety applications, etc Whitehead (2004); Niyato et al. (2011); Zhang et al. (2012); Aijaz and Aghvami (2015).

The implementation of huge numbers of sensors with different traffic requirements creates several challenges such as accessing the spectrum, communicating easily with other machines and meeting the increased energy requirement. The spectrum resources become scarce with the proliferation of wireless devices that support very high data rate services. Therefore, spectrum access technology can be adopted to utilize the spectrum more efficiently with controlled interference techniques to reduce the impact on authorized users. Cognitive M2M (CM2M) has been proposed very recently to enhance the efficiency and reliability of M2M communications Zhang et al. (2012); Aijaz and Aghvami (2015). In a CM2M, there are usually two systems utilizing the same frequency range: the primary and secondary systems Mitola and Maguire (1999); Haykin (2005). The primary system refers to the system that has the unlimited access to the licensed spectrum Nekovee (2010). While the secondary system dynamically access the same spectrum using one of the well-known spectrum sharing paradigms; interweave, overlay, and underlay modes to limit and control its interference on the primary system. Thus, CM2M can improve the spectrum utilization by giving different machines the opportunity to exploit under-utilized spectrum bands while meeting the energy and service quality requirements Zhang et al. (2012); Aijaz and Aghvami (2015). In Zhang et al. (2012) Zhang, et. al introduced the cognitive dimension to M2M to enhance the performance of conventional M2M commuincations. They discussed the motivations to use CM2M communications and the applications of the new paradigm in different fields. In Aijaz and Aghvami (2015), the authors investigated CM2M communications from a protocol stack perspective, the challenges, standardization efforts, and the latest developments in the Physical, MAC, and Transport layers. The research in CM2M communications still needs continuous improvement in spectrum access, coverage extensions and efficient energy utilization.

Cooperative diversity has been proposed to combat channel fading, enhance the throughput and increase the coverage of wireless networks Sendonaris et al. (2003a); Laneman et al. (2004). Cooperative relaying is very useful in the context of IoT as it allows low power equipments to achieve longer transmission ranges with higher throughput while reducing the energy consumption of those devices hence prologing their batteries lifetime. Incremental decode-and-forward cooperative relaying has been shown to improve the spectral efficiency of wireless networks compared to conventional decode-and-forward relaying by limiting cooperation to cases where relaying is needed depending on the status of the direct link Laneman et al. (2004); Ikki and Ahmed (2011); Tourki et al. (2013).

In this paper, we propose a generalized cooperative spectrum sharing (GCSS) scheme for CM2M communication to address the challenges of conventional CM2M communications by reaping the benefits of machine cooperation. The GCSS scheme aims to use machine cooperation to extend the current network coverage and transfer information messages between other related nodes. Different available machines can be used to relay the required information in the same shared spectrum, whereas, improving the link reliability may not be the only design criterion for the CM2M network. Specifically, other design criterion can affect the machine relaying choices such as security, energy consumption, scheduling and load balancing. Therefore, we provide a generalized analysis for underlaid machine selection scheme to evaluate possible performance limits in the CM2M network. To this end, we provide exact outage performance analysis for delivering specific information using different possible machines that share the spectrum of other authorized machines/users. To the best of our knowledge incremental relaying with generalized order relay selection in CM2M has not been studied in literature.

4.2 System Model

Consider a CM2M network that is designed to access the licensed spectrum of a primary network without affecting its performance. The CM2M network consists of a transmitting machine that is introduced as a secondary source (SS), a receiver that is known as a secondary destination (SD), and a cluster of M available relaying machines that can be used to forward the information to the SD if needed, as shown in Fig. 6.1. The CM2M network needs to restrict its activity in order not to affect the reception quality at the primary receiver (PR). On the other hand, we assume that the primary source is located far from the SD and relaying machine, thus the interference from the primary network can be neglected. The secondary CM2M network uses incremental decode-and-forward relaying strategy with a generalized-order relay selection based on SNR. Based on the adopted strategy, the SS attempts initially to deliver the required information without the help of the relaying machines. If the information can not be delivered successfully using the direct transmission, the SS will seek the help of one of the relaying machines. The candidate relay is selected from the successful detection set (D) to forward the source message in the second transmission phase. The selection of the N^{th} best relay can be done either in a centralized node or in a distributed manner using timers as described in Bletsas et al. (2007). The selected relaying machine is not necessary the one that improves the end-to-end signal-to-noise ratio (SNR), thus we assume a general N^{th} best relaying machine. The criterion of selecting the relay in such dynamic dense network is expected to change according to different conditions. Therefore, the generalized N^{th} best relaying strategy represent a worst performance limit.

In our system, We assume flat fading channels that are modelled as a zero mean complex Gaussian random variables. We denote the channel between the SS and SD as h_{SD}, the channel between the SS and the i^{th} relay is defined as $h_{\mathrm{SR_i}}$ while the channel between the i^{th} secondary relay and the SD is denoted as $h_{\mathrm{R_iD}}$. As for the interference channel between the SS and the selected relay to the PR, they are defined as h_{SP} and h_{RP} respectively. Moreover, we have $\mathbb{E}\left[|h_{\mathrm{SD}}|^2\right] \propto [d_{\mathrm{SD}}^{-\alpha}]$, $\mathbb{E}\left[|h_{\mathrm{SR_i}}|^2\right] \propto [d_{\mathrm{SR_i}}^{-\alpha}]$, $\mathbb{E}\left[|h_{\mathrm{R_iD}}|^2\right] \propto [d_{\mathrm{R_iD}}^{-\alpha}]$,

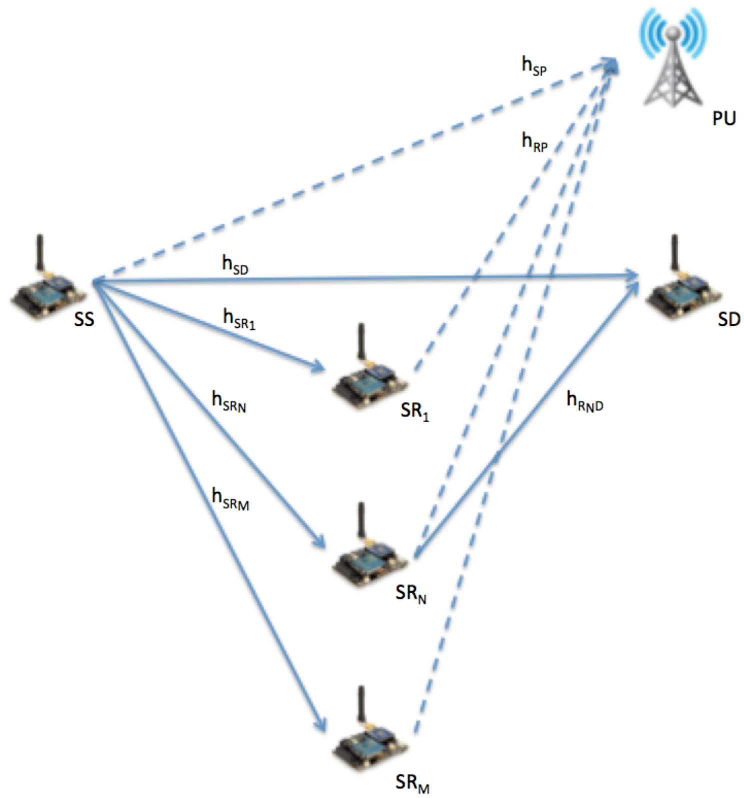

Figure 4.1. System model for the GCSS Scheme in a CM2M network.

$\mathbb{E}\left[|h_{\mathrm{SP}}|^2\right] \propto [d_{\mathrm{SP}}^{-\alpha}]$, $\mathbb{E}\left[|h_{\mathrm{RP}}|^2\right] \propto [d_{\mathrm{RP}}^{-\alpha}]$, where d_{ij} is the distance between nodes i and j, α is the path loss exponent, and $\mathbb{E}[.]$ is the statistical average. As a result of having a cluster of relays, the relays are assumed to be close to each other so $d_{\mathrm{SR}_i} = d_{\mathrm{SR}}$ and $d_{\mathrm{R}_i\mathrm{D}} = d_{\mathrm{RD}}$ and thus the channels between the SS and the relays, and the channels between the relays and the SD are independent and identically distributed (iid). The proposed CM2M needs a limited feedback channel that acknowledge the SS and relays with the success or failure of the direct transmission, therefore, we assume a robust feedback channels between the aforementioned nodes.

The CM2M operates using underlay spectrum sharing paradigm where the secondary and primary networks transmit simultaneously on the same spectrum. The transmission power of the secondary nodes has to be adjusted so that the interference at the primary receiver is kept below a peak interference threshold Q. Thus, the maximum transmit power of the SS is given by

$$P_{\text{S}} = \frac{Q}{|h_{\text{SP}}|^2}. \tag{4.1}$$

Similarly, the transmit power of the secondary relay can be written as

$$P_{\text{R}} = \frac{Q}{|h_{\text{RP}}|^2}. \tag{4.2}$$

After the first transmission phase, the transmitted signal with power P_{S} is received at the destination as,

$$y_{\text{SD}} = \sqrt{P_{\text{S}}} h_{\text{SD}} x + n_{\text{SD}}, \tag{4.3}$$

where x is the signal transmitted by the SS and n_{SD} is complex additive white Gaussian noise (AWGN) with zero mean and variance N_0, i.e., $n_{\text{SD}} \sim \mathcal{CN}(0, N_0)$. As for the received signal at the relay is given as

$$y_{\text{SR}_i} = \sqrt{P_{\text{S}}} h_{\text{SR}_i} x + n_{\text{SR}_i} \tag{4.4}$$

where $n_{\text{SR}_i} \sim \mathcal{CN}(0, N_0)$ is the noise at the i^{th} relay.

If the destination decodes the source's message correctly, the destination will broadcast a feedback indicating the success of the transmission. Then, the SS can then broadcast the subsequent message in the next transmission phase. Otherwise, if the SNR of the direct link between the SS and the SD falls below the decoding threshold, the SD will broadcast a feedback indicating the failure of the transmission and announce the need of retransmission. As a result, the relay with the N^{th} best SNR on the relay-destination link is selected to forward the message to the destination in the second transmission phase. It is worth to mention that the retransmission is possible if at least one relay could decode the source message successfully, otherwise we have an outage. Moreover, N can not be greater than the number of the relays in the decoding set, outage is reported. The signal received at the SD from the cooperative transmission in the second transmission phase is given as

$$y_{\mathrm{R}_i\mathrm{D}} = \sqrt{P_{\mathrm{R}}} h_{\mathrm{R}_i\mathrm{D}} x + n_{\mathrm{R}_i\mathrm{D}} \tag{4.5}$$

where $n_{\mathrm{R}_i\mathrm{D}} \sim \mathcal{CN}(0, N_0)$ is the noise at the SD. The destination then combines both copies, y_{SD} received from the SS after the first transmission phase and $y_{\mathrm{R}_i\mathrm{D}}$ received from the N^{th} best relay in the second transmission phase using maximal ratio combining (MRC) technique.

The SNRs of the source-destination, source-relay, relay-destination links denoted as $\gamma_{\mathrm{SD}}, \gamma_{\mathrm{SR}}$, and γ_{RD} are given as

$$\begin{aligned}\gamma_{\mathrm{SD}} &= \frac{P_{\mathrm{S}}|h_{\mathrm{SD}}|^2}{N_0}\\ \gamma_{\mathrm{SR}} &= \frac{P_{\mathrm{S}}|h_{\mathrm{SR}}|^2}{N_0}\\ \gamma_{\mathrm{RD}} &= \frac{P_{\mathrm{R}}|h_{\mathrm{RD}}|^2}{N_0}\end{aligned} \tag{4.6}$$

It is clear that the SNRs are functions of P_{S} and P_{R} which are random variables. In our analysis we will start by formulating the outage probability conditioned on P_S and P_R then will take the expectation on them to complete our analysis.

4.3 Outage Performance of the CM2M system

In the GCSS scheme with incremental cooperative relaying, the outage takes place when the instantaneous rate of the end-to-end falls below a predefined spectral efficiency threshold R_{S} in bits per second per hertz. The outage occurs when the direct transmission fails to support R_{S} bit/s/Hz and $\mathcal{D}$ is empty, or when the direct and relaying transmission links (when the any relay detect the signal successfully) can not deliver together the required rate. Therefore, the outage probability is expressed for a given P_{S} and P_{R} as follows

$$P_{\mathrm{out}|P_{\mathrm{S}},P_{\mathrm{R}}} = \sum_{k=0}^{N-1} \binom{M}{k} P_{\mathrm{out}|\mathcal{D}=\mathcal{D}_k,P_{\mathrm{S}}} \Pr\left(\mathcal{D}=\mathcal{D}_k |\, P_{\mathrm{S}}\right) +$$
$$\sum_{k=N}^{M} \binom{M}{k} P_{\mathrm{out}|\mathcal{D}=\mathcal{D}_k,P_{\mathrm{S}},P_{\mathrm{S}}} \Pr\left(\mathcal{D}=\mathcal{D}_k |\, P_{\mathrm{S}}, P_{\mathrm{R}}\right). \tag{4.7}$$

To evaluate different terms in (4.7), we consider the following different cases for a given P_{S} and P_{R}:

4.3.1 **Case I:** ($\mathcal{D} = \emptyset$)

This is the case when none of the M relays was able to successfully decode the source message in the first transmission phase leaving the decoding set empty. This is represented from an information theoretic point of view by the event of the rate of the transmission falling below the threshold rate, this can be written as $\frac{1}{2}\log(1+\gamma_{\mathrm{SR}}) < R_{\mathrm{S}}$, where the factor 1/2 accounts for the fact that two transmission phases are needed to complete each transmission. The probability of this event, $\mathcal{D} = \emptyset$ is given as

$$\begin{aligned}
\Pr(\mathcal{D}=\emptyset|P_{\mathrm{S}}) &= \Pr\left[\frac{1}{2}\log\left(1+\gamma_{\mathrm{SR}_i}\right) < R_{\mathrm{S}}\right] \\
&= \Pr\left[\frac{1}{2}\log\left(1+\frac{P_S|h_{SR_i}|^2}{N_0}\right) < R_S\right] \\
&= \prod_{i=1}^{M} \Pr\left[\frac{P_S|h_{\mathrm{SR_i}}|^2}{N_0} < 2^{2R_S}-1\right] \\
&= \left(\Pr\left[|h_{SR}|^2 < \frac{u_2 N_0}{P_{\mathrm{S}}}\right]\right)^M \\
&= \left(1-e^{-\frac{u_2 N_0}{\mu_{\mathrm{SR}} P_{\mathrm{S}}}}\right)^M
\end{aligned} \tag{4.8}$$

where $u_2 = 2^{2R_{\mathrm{S}}} - 1$, and assuming i.i.d. Rayleigh fading channels.

Outage event occurs in this case, i.e. $\mathcal{D} = \emptyset$, when the SNR at the destination falls below the threshold SNR. Since none of the relays participates in forwarding the source message then the SNR at the destination in this case will be equal to γ_{SD} given in eq. (6.4). The outage probability is given as

$$\begin{aligned} P_{\mathrm{out}|\mathcal{D}=\emptyset,P_{\mathrm{S}}} &= \Pr\left[\log\left(1+\frac{P_{\mathrm{S}}|h_{\mathrm{SD}}|^2}{N_0}\right) < R_{\mathrm{S}}\right] \\ &= \Pr\left[|h_{\mathrm{SD}}|^2 < \frac{u_1 N_0}{P_{\mathrm{S}}}\right] \\ &= 1 - e^{-\frac{u_1 N_0}{\mu_{\mathrm{SD}} P_{\mathrm{S}}}} \end{aligned} \tag{4.9}$$

where $u_1 = 2^{R_{\mathrm{S}}} - 1$.

4.3.2 **Case II:** $(\mathcal{D} = \mathcal{D}_k)$

In this case, k out of the M relays are able to successfully decode the source message in the first transmission phase, the probability of this event is given as

$$\begin{aligned} &\Pr\left(\mathcal{D} = \mathcal{D}_k | P_{\mathrm{S}}\right) \\ &= \Pr\Bigg[\frac{1}{2}\log\left(1+\frac{P_{\mathrm{S}}\left|h_{SR_i}\right|^2}{N_0}\right) \geq R_{\mathrm{S}}, \forall i \in \mathcal{D}_k, \\ &\qquad \frac{1}{2}\log\left(1+\frac{P_{\mathrm{S}}\left|h_{\mathrm{SR_j}}\right|^2}{N_0}\right) < R_{\mathrm{S}}, \forall j \in \overline{\mathcal{D}}_k\Bigg] \\ &= \Pr\left[\left|h_{\mathrm{SR}_i}\right|^2 \geq \tfrac{u_2 N_0}{P_{\mathrm{S}}}, \forall i \in \mathcal{D}_k, \left|h_{\mathrm{SR}_j}\right|^2 < \tfrac{u_2 N_0}{P_{\mathrm{S}}}, \forall j \in \overline{\mathcal{D}}_k\right] \\ &= \Pr\left[\left|h_{SR_i}\right|^2 \geq \tfrac{u_2 N_0}{P_S}, \forall i \in \mathcal{D}_k\right] \Pr\left[\left|h_{SR_j}\right|^2 < \tfrac{u_2 N_0}{P_{\mathrm{S}}}, \forall j \in \overline{D}_k\right] \\ &= \prod_{i \in D_k} \Pr\left(\left|h_{\mathrm{SR}_i}\right|^2 \geq \tfrac{u_2 N_0}{P_{\mathrm{S}}}\right) \prod_{j \in \overline{D}_k} \Pr\left(\left|h_{\mathrm{SR}_j}\right|^2 < \tfrac{u_2 N_0}{P_{\mathrm{S}}}\right) \\ &= \left(e^{-\frac{u_2 N_0}{\mu_{\mathrm{SR}} P_{\mathrm{S}}}}\right)^k \left(1 - e^{-\frac{u_2 N_0}{\mu_{\mathrm{SR}} P_{\mathrm{S}}}}\right)^{M-k} \end{aligned} \tag{4.10}$$

If the destination signals a need for retransmission then the relay with N^{th} best SNR on the link between itself and the destination is selected to retransmit the source message in the second transmission phase. The selection criterion for our model can be written as $\mathrm{SR}_N = \arg\ N^{\mathrm{th}}\max_{i \in \mathcal{D}_k} \left(\frac{P_{\mathrm{R}}\left|h_{\mathrm{R}_i\mathrm{D}}\right|^2}{N_0}\right)$ and the instantaneous SNR of the N^{th} best relay,γ_N , is given as

$$\gamma_N = N^{\text{th}} \max_{i \in \mathcal{D}_k} \left(\frac{P_{\text{R}} \left| h_{\text{R}_i\text{D}} \right|^2}{N_0} \right) \tag{4.11}$$

The outage event in this case occurs in two cases:

4.3.2.1 **Case II(a)** $K < N$

In this case the number of relays in the decoding set is smaller than the order of the selected relay N, that means that none of the relays will forward the source message and therefore the total SNR at the destination is equal to γ_{SD} given in eq. (6.4), and the outage probability is the same as the outage probability given in eq. (4.9).

4.3.2.2 **Case II(b)** $N \leq K \leq M$

In this case the number of relays in the decoding set is at least equal to the order of selection N but outage event occurs when the total instantaneous rate at the secondary destination combined from transmissions on both links, direct and relay, falls below a defined threshold. The outage probability can be represented as follows

$$\begin{aligned}
&P_{\text{out}|D=D_k,P_{\text{S}},P_{\text{R}}} \\
&= \Pr\left[\log\left(1+\gamma_{\text{SD}}\right) < R_{\text{S}}, \tfrac{1}{2}\log\left(1+\gamma_{\text{SD}}+\gamma_N\right) < R_{\text{S}}\right] \\
&= \Pr\left[\gamma_{\text{SD}} < u_1, \gamma_{\text{SD}}+\gamma_N < u_2\right] \\
&= \int_0^{u_1} F_{\gamma_N}\left(u_2 - x\right) f_X\left(x\right) dx \\
&= \int_{1-\frac{u_1}{u_2}}^{1} F_Y\left(u_2 x'\right) f_X\left(x'\right) u_2 dx'
\end{aligned} \tag{4.12}$$

where $X = \gamma_{\mathrm{SD}}$ and $f_X(x) = \frac{1}{\lambda_{\mathrm{SD}}} e^{-\frac{x}{\lambda_{\mathrm{SD}}}}$, where $\lambda_{\mathrm{SD}} = \frac{\mu_{\mathrm{SD}} P_{\mathrm{S}}}{N_0}$, and $Y = \gamma_N$, and the CDF of the N^{th} best SNR from Ikki and Ahmed (2009c) can be written as

$$\begin{aligned}
F_Y(y) &= \sum_{n=1}^{N} \binom{k}{n-1} [F_{\gamma_{\mathrm{RD}}}(y)]^{k-n+1} [1 - F_{\gamma_{\mathrm{RD}}}(y)]^{n-1} \\
&= \sum_{n=1}^{N} \left(\begin{array}{c} k \\ \\ n-1 \end{array} \right) \left(1 - e^{-\frac{y}{\lambda_{\mathrm{RD}}}}\right)^{k-n+1} \left(e^{-\frac{y}{\lambda_{\mathrm{RD}}}}\right)^{n-1} \\
&= 1 + \sum_{n=1}^{N} \sum_{\substack{m=0 \\ n+m>1}}^{k-n+1} (-1)^m \left(\begin{array}{c} k \\ \\ n-1 \end{array} \right) \left(\begin{array}{c} k-n+1 \\ \\ m \end{array} \right) e^{-\frac{(m+n-1)y}{\lambda_{\mathrm{RD}}}}
\end{aligned} \tag{4.13}$$

where $F_{\gamma_{\mathrm{RD}}}(y)$ is the CDF of the SNR of the relay-destination link and is given as $F_{\gamma_{\mathrm{RD}}}(y) = 1 - e^{-\frac{y}{\lambda_{\mathrm{RD}}}}$ where $\lambda_{\mathrm{RD}} = \frac{P_R \mu_{\mathrm{RD}}}{N_0}$.

By substituting eq.(6.9) into eq.(6.8) we obtain $P_{\mathrm{out}|D=D_k, P_{\mathrm{S}}, P_{\mathrm{R}}}$, which can be written as following

$$\begin{aligned}
&P\left(out|\, D = D_k, P_S, P_R\right) = \int_{1-\frac{u_1}{u_2}}^{1} F_Y\left(u_2 x'\right) f_X\left(x'\right) u_2 dx' \\
&= \int_{1-\frac{u_1}{u_2}}^{1} \left[1 + \sum_{n=1}^{N} \sum_{\substack{m=0 \\ n+m>1}}^{k-n+1} (-1)^m \left(\begin{array}{c} k \\ \\ n-1 \end{array} \right) \left(\begin{array}{c} k-n+1 \\ \\ m \end{array} \right) \left(e^{-\frac{(m+n-1)u_2 x'}{\lambda_{RD}}} \right) \right] \\
&\left[\frac{u_2}{\lambda_{SD}} \left(e^{-\frac{(1-x')u_2}{\lambda_{SD}}} \right) \right] dx'
\end{aligned} \tag{4.14}$$

For the sake of simplification we can write $P_{\mathrm{out}|D=D_k, P_{\mathrm{S}}, P_{\mathrm{R}}} = I_1 + I_2$. Then by solving for I_1 and I_2 we get the following expressions

$$I_1 = \int\limits_{1-\frac{u_1}{u_2}}^{1} \frac{u_2}{\lambda_{\mathrm{SD}}} \left(e^{-\frac{(1-x')u_2}{\lambda_{\mathrm{SD}}}} \right) dx' = 1 - e^{-\frac{u_1}{\lambda_{\mathrm{SD}}}} \tag{4.15}$$

$$\begin{aligned} I_2 &= \int\limits_{1-\frac{u_1}{u_2}}^{1} \left(\tfrac{u_2}{\lambda_{\mathrm{SD}}} e^{-\frac{(1-x')u_2}{\lambda_{\mathrm{SD}}}} \Sigma_1 e^{-\frac{(m+n-1)u_2 x'}{\lambda_{\mathrm{RD}}}} \right) dx' \\ &= \Sigma_1 \tfrac{\lambda_{\mathrm{RD}}}{\lambda_{\mathrm{RD}} - \lambda_{\mathrm{SD}}(m+n-1)} e^{-\frac{u_2(m+n-1)}{\lambda_{\mathrm{RD}}}} \left[1 - e^{-\frac{u_1 \left(\lambda_{\mathrm{RD}} - \lambda_{\mathrm{SD}}(m+n-1) \right)}{\lambda_{\mathrm{SD}} \lambda_{\mathrm{RD}}}} \right] \end{aligned} \tag{4.16}$$

where $\Sigma_1 = \sum\limits_{n=1}^{N} \sum\limits_{\substack{m=0 \\ n+m>1}}^{k-n+1} (-1)^m \binom{k}{n-1} \binom{k-n+1}{m}$

4.3.3 Average Outage Probability

We find the expression for the total average outage probability by taking the expectation for the conditional probability in eq.(4.7) with respect to P_S and P_R as follows

$$\begin{aligned} P_{\mathrm{out}} &= \mathbb{E}_{P_{\mathrm{S}}, P_{\mathrm{R}}} \left[P_{\mathrm{out}|P_{\mathrm{S}}, P_{\mathrm{R}}} \right] \\ &= \sum_{k=0}^{N-1} \binom{M}{k} \underbrace{\mathbb{E}_{P_{\mathrm{S}}} \left[P_{\mathrm{out}|\mathcal{D}=\mathcal{D}_k, P_{\mathrm{S}}} \Pr \left(\mathcal{D} = \mathcal{D}_k | \, P_{\mathrm{S}} \right) \right]}_{E_1} + \\ \sum_{k=N}^{M} \binom{M}{k} & \underbrace{\mathbb{E}_{P_{\mathrm{S}}, P_{\mathrm{R}}} \left[P_{\mathrm{out}|\mathcal{D}=\mathcal{D}_k, P_{\mathrm{S}}, P_{\mathrm{R}}} \Pr \left(\mathcal{D} = \mathcal{D}_k | \, P_{\mathrm{S}}, P_{\mathrm{R}} \right) \right]}_{E_2} . \end{aligned} \tag{4.17}$$

First, we find E_1 that is equivalent to the following expression

$$E_1 = \mathbb{E}_{P_{\mathrm{S}}} \left[\left(1 - e^{-\frac{u_1 N_0}{\mu_{\mathrm{SD}} P_{\mathrm{S}}}} \right) \left(e^{-\frac{u_2 N_0 k}{\mu_{\mathrm{SR}} P_{\mathrm{S}}}} \right) \left(1 - e^{-\frac{u_2 N_0}{\mu_{\mathrm{SR}} P_{\mathrm{S}}}} \right)^{M-k} \right], \tag{4.18}$$

where P_{S} is given in eq.(6.1). First let $X = |h_{\mathrm{SP}}|^2$, where X is a random variable with PDF $f_X(x) = \frac{1}{\mu_{\mathrm{SP}}} e^{-\frac{x}{\mu_{\mathrm{SP}}}}$. Then by rewriting eq. (4.18) in terms of random variable X and averaging it over X, E_1 is given as

$$E_1 = \int_0^\infty \left(1 - e^{-\frac{u_1 N_0}{\mu_{\mathrm{SD}} Q} y}\right)\left(1 - e^{-\frac{u_2 N_0}{\mu_{\mathrm{SR}} Q} y}\right)^{M-k} \frac{1}{\mu_{\mathrm{SP}}} e^{-\frac{y}{\mu_{\mathrm{SP}}}} dy$$
$$= \frac{1}{\mu_{SP}} \int_0^\infty \left(1 - e^{-\frac{u_1 N_0}{\mu_{SD} Q} y}\right) \sum_{r=0}^{M-k} (-1)^r \binom{M-k}{r} e^{-\frac{u_2 N_0 (k+r)}{\mu_{SR} Q} y} e^{-\frac{y}{\mu_{SP}}} dy$$
$$= \sum_{r=0}^{M-k} (-1)^r \binom{M-k}{r} \left[\frac{\mu_{\mathrm{SR}} Q}{(u_2 \mu_{\mathrm{SP}} N_0 (k+r) + \mu_{\mathrm{SR}} Q)} - \right.$$
$$\left. \frac{\mu_{\mathrm{SD}} \mu_{\mathrm{SR}} \mu_{\mathrm{SP}} Q}{(u_1 \mu_{\mathrm{SR}} \mu_{\mathrm{SP}} N_0 + u_2 \mu_{\mathrm{SD}} \mu_{\mathrm{SP}} N_0 (k+r) + \mu_{\mathrm{SD}} \mu_{\mathrm{SR}} Q)}\right] \tag{4.19}$$

Secondly, to calculate E_2, we find the following expectation

$$E_2 = \mathbb{E}_{P_{\mathrm{S}}, P_{\mathrm{R}}} \left[g_1(P_{\mathrm{S}}, P_{\mathrm{R}}) + g_2(P_{\mathrm{S}}, P_{\mathrm{R}})\right] \tag{4.20}$$

where $g_1(P_{\mathrm{S}}, P_{\mathrm{R}})$ is given as

$$g_1(P_{\mathrm{S}}, P_{\mathrm{R}}) = \left(1 - e^{-\frac{u_1}{\lambda_{\mathrm{SD}}}}\right)\left(e^{-\frac{u_2 N_0 k}{\mu_{\mathrm{SR}} P_{\mathrm{S}}}}\right) \Sigma_2 e^{-\frac{u_2 N_0 a}{\mu_{\mathrm{SR}} P_{\mathrm{S}}}} \tag{4.21}$$

and $g_2(P_{\mathrm{S}}, P_{\mathrm{R}})$ is expressed as

$$g_2(P_{\mathrm{S}}, P_{\mathrm{R}}) = \Sigma_1 \frac{\frac{P_{\mathrm{R}} \mu_{\mathrm{RD}}}{N_0}}{\frac{P_{\mathrm{R}} \mu_{\mathrm{RD}}}{N_0} - \frac{P_{\mathrm{S}} \mu_{\mathrm{SD}} (m+n-1)}{N_0}} \left(e^{-\frac{u_2 (m+n-1) N_0}{P_{\mathrm{R}} \mu_{\mathrm{RD}}}}\right)$$
$$\left(1 - e^{-\frac{u_1 \left(\frac{P_{\mathrm{R}} \mu_{\mathrm{RD}}}{N_0} - \frac{P_{\mathrm{S}} \mu_{\mathrm{SD}} (m+n-1)}{N_0}\right)}{\frac{P_{\mathrm{S}} \mu_{\mathrm{SD}}}{N_0} \frac{P_{\mathrm{R}} \mu_{\mathrm{RD}}}{N_0}}}\right) e^{-\frac{u_2 N_0 k}{P_{\mathrm{S}} \mu_{\mathrm{SR}}}} \Sigma_2 e^{-\frac{u_2 N_0 a}{P_{\mathrm{S}} \mu_{\mathrm{SR}}}} \tag{4.22}$$

with $\Sigma_2 = \sum_{a=0}^{M-k} (-1)^a \binom{M-k}{a}$ and P_{R} is given in eq.(6.2). Now, let $Y = |h_{\mathrm{RP}}|^2$, where Y is a random variable with PDF $f_Y(y) = \frac{1}{\mu_{\mathrm{RP}}} e^{-\frac{y}{\mu_{\mathrm{RP}}}}$.

To find E_2, we evaluate $E_{21} = E_{P_S,P_R}[g_1(P_{\mathrm{S}}, P_{\mathrm{R}})]$ and $E_2 = E_{P_{\mathrm{S}},P_{\mathrm{R}}}[g_2(P_{\mathrm{S}}, P_{\mathrm{R}})]$ in the following discussion.

First, we derive an expression for E_{21} by substituting for $P_{\mathrm{S}} = \frac{Q}{x}$ in eq. (4.21), and taking the expectation for $g_1(P_S, P_R)$, E_{21} that gives

$$E_{21} = \Sigma_2 \Bigg[\left(\frac{1}{\frac{u_2 N_0 (k+a)}{Q \mu_{\mathrm{SR}}} + \frac{1}{\mu_{\mathrm{SP}}}} \right) - \left(\frac{1}{\frac{1}{Q}\left(\frac{u_1 N_0}{\mu_{\mathrm{SD}}} + \frac{u_2 N_0 (k+a)}{\mu_{\mathrm{SR}}}\right) + \frac{1}{\mu_{\mathrm{SP}}}} \right) \Bigg] \tag{4.23}$$

As for E_{22}, we substitute $P_{\mathrm{S}} = \frac{Q}{X}$ and $P_{\mathrm{R}} = \frac{Q}{Y}$ into eq. (4.22), and set $\alpha_{\mathrm{SD}} = \frac{Q\mu_{\mathrm{SD}}}{N_0}$, $\alpha_{\mathrm{SR}} = \frac{Q\mu_{\mathrm{SR}}}{N_0}$, and $\alpha_{\mathrm{RD}} = \frac{Q\mu_{\mathrm{RD}}}{N_0}$ to simplify the calculations. After some rearrangements, E_{22} is simplified as in eq. (4.24).

$$E_{22} = \Sigma_1 \frac{1}{\mu_{\mathrm{SP}}\mu_{\mathrm{RP}}} \int_0^{\infty} \frac{\alpha_{\mathrm{RD}}}{\alpha_{SD}(m+n-1)} x \sum_{b=0}^{1} (-1)^b \binom{1}{b} \sum_{a=0}^{M-k} (-1)^a \binom{M-k}{a} e^{-\left(\frac{u_1 \alpha_{\mathrm{SR}} b \mu_{\mathrm{SP}} + u_2 \alpha_{\mathrm{SD}} (k+a) \mu_{\mathrm{SP}} + \alpha_{\mathrm{SD}}\alpha_{\mathrm{SR}}}{\alpha_{\mathrm{SD}}\alpha_{\mathrm{SR}}\mu_{\mathrm{SP}}}\right)x} \underbrace{\int_0^{\infty} \frac{1}{\frac{\alpha_{\mathrm{RD}}}{\alpha_{\mathrm{SD}}(m+n-1)}x - y} e^{-\left(\frac{(u_2 - u_1 b)(m+n-1)\mu_{\mathrm{RP}} + \alpha_{\mathrm{RD}}}{\alpha_{\mathrm{RD}}\mu_{\mathrm{RP}}}\right)y} dy}_{I_3} \, dx \tag{4.24}$$

The term I_3 can be written as

$$I_3 = \int_0^{\infty} \frac{1}{c_1 - y} e^{-c_2 y} dy \tag{4.25}$$

where c_1 and c_2 are defined as

$$c_1 = \frac{\alpha_{\mathrm{RD}} x}{\alpha_{\mathrm{SD}}(m+n-1)}$$
$$c_2 = \frac{(u_2 - u_1 b)(m+n-1)\mu_{\mathrm{RP}} + \alpha_{\mathrm{RD}}}{\alpha_{\mathrm{RD}}\mu_{\mathrm{RP}}} \tag{4.26}$$

A tractable mathematical expression can be found by rearranging the terms and using (Gradshteyn and Ryzhik, 2014, eq. (3.351.4)) as

$$I_3 = e^{-c_1 c_2}\,\mathrm{Ei}(c_1 c_2) \tag{4.27}$$

where Ei is the Exponential Integral and is defined in (Gradshteyn and Ryzhik, 2014, eq. (8.211.1)). By subsituting eq. (4.27) into eq. (4.24), then E_{22} can be written as

$$E_{22} = \Sigma_1 \tfrac{1}{\mu_{\mathrm{SP}}\mu_{\mathrm{RP}}} \left(\tfrac{\alpha_{\mathrm{RD}}}{\alpha_{\mathrm{SD}}(m+n-1)}\right) \sum_{b=0}^{1} (-1)^b \binom{1}{b} \Sigma_2 \underbrace{\int_0^\infty x e^{-c_3 x} e^{c_4 x}\,\mathrm{Ei}(c_4 x)dx}_{I_4} \tag{4.28}$$

where c_3 and c_4 are expressed as

$$c_3 = \frac{u_1 \alpha_{\mathrm{SR}} b \mu_{\mathrm{SP}} + u_2 \alpha_{\mathrm{SD}}(k+a)\mu_{\mathrm{SP}} + \alpha_{\mathrm{SD}}\alpha_{\mathrm{SR}}}{\alpha_{SD}\alpha_{SR}\mu_{\mathrm{SP}}} \tag{4.29}$$

$$c_4 = \frac{c_1 c_2}{x} = \tfrac{(u_2 - u_1 b)(m+n-1)\mu_{\mathrm{RP}} + \alpha_{\mathrm{RD}}}{\alpha_{\mathrm{SD}}\mu_{\mathrm{RP}}(m+n-1)}. \tag{4.30}$$

The integration I_4 can be found by using (Geller and Ng, 1969, eq.(4.2.15)) as follows

$$I_4 = -\tfrac{1}{(c_3+c_4)^2}\left[\ln\left(\tfrac{c_3+c_4}{c_4} - 1\right) - \tfrac{c_3+c_4}{c_3}\right]. \tag{4.31}$$

Thus, E_{22} can be evaluated by substituting I_4, c_3 and c_4 in eq.(4.28).

$$E_{22} = -\sum_{n=1}^{N} \sum_{\substack{m=0 \\ m+n>1}}^{k-n+1} (-1)^m \begin{pmatrix} k \\ n-1 \end{pmatrix} \begin{pmatrix} k-n+1 \\ m \end{pmatrix} \left(\tfrac{1}{\mu_{SP}\mu_{RP}}\right)\left(\tfrac{\alpha_{RD}}{\alpha_{SD}(m+n-1)}\right)$$
$$\sum_{b=0}^{1} (-1)^b \binom{1}{b} \sum_{a=0}^{M-k} (-1)^a \binom{M-k}{a} \left(\tfrac{1}{(c_3+c_4)^2}\left[\ln\left(\tfrac{c_3+c_4}{c_4} - 1\right) - \tfrac{c_3+c_4}{c_3}\right]\right) \tag{4.32}$$

$$E_{22} = -\sum_{n=1}^{N} \sum_{\substack{m=0 \\ m+n>1}}^{k-n+1} (-1)^m \begin{pmatrix} k \\ n-1 \end{pmatrix} \begin{pmatrix} k-n+1 \\ m \end{pmatrix} \left(\frac{1}{\mu_{SP}\mu_{RP}}\right) \left(\frac{\alpha_{RD}}{\alpha_{SD}(m+n-1)}\right) \sum_{b=0}^{1} (-1)^b \binom{1}{b}$$
$$\sum_{a=0}^{M-k} (-1)^a \binom{M-k}{a} \left(\frac{1}{\left(\frac{u_1\alpha_{SR}b\mu_{SP}+u_2\alpha_{SD}(k+a)\mu_{SP}+\alpha_{SD}\alpha_{SR}}{\alpha_{SD}\alpha_{SR}\mu_{SP}} + \frac{(u_2-u_1b)(m+n-1)\mu_{RP}+\alpha_{RD}}{\alpha_{SD}\mu_{RP}(m+n-1)}\right)^2} \right.$$
$$\left[\ln\left(\frac{\frac{u_1\alpha_{SR}b\mu_{SP}+u_2\alpha_{SD}(k+a)\mu_{SP}+\alpha_{SD}\alpha_{SR}}{\alpha_{SD}\alpha_{SR}\mu_{SP}} + \frac{(u_2-u_1b)(m+n-1)\mu_{RP}+\alpha_{RD}}{\alpha_{SD}\mu_{RP}(m+n-1)}}{\frac{(u_2-u_1b)(m+n-1)\mu_{RP}+\alpha_{RD}}{\alpha_{SD}\mu_{RP}(m+n-1)}} - 1 \right) \right.$$
$$\left. \left. - \frac{\frac{u_1\alpha_{SR}b\mu_{SP}+u_2\alpha_{SD}(k+a)\mu_{SP}+\alpha_{SD}\alpha_{SR}}{\alpha_{SD}\alpha_{SR}\mu_{SP}} + \frac{(u_2-u_1b)(m+n-1)\mu_{RP}+\alpha_{RD}}{\alpha_{SD}\mu_{RP}(m+n-1)}}{\frac{u_1\alpha_{SR}b\mu_{SP}+u_2\alpha_{SD}(k+a)\mu_{SP}+\alpha_{SD}\alpha_{SR}}{\alpha_{SD}\alpha_{SR}\mu_{SP}}} \right] \right)$$
$$(4.33)$$

Finally, the end-to-end average outage probability is found using E_{22} and E_{21} to obtain E_2 and by substituting E_1 from eq.(4.19) and E_2 into eq.(4.17) obtaining eq. (4.34) on the next page.

$$
\begin{aligned}
P_{\text{out}} = & \sum_{k=0}^{N-1} \binom{M}{k} \sum_{r=0}^{M-k} (-1)^r \binom{M-k}{r} \\
& \left[\frac{\mu_{\text{SR}} Q}{(u_2 \mu_{\text{SP}} N_0 (k+r) + \mu_{\text{SR}} Q)} - \frac{\mu_{\text{SD}} \mu_{\text{SR}} \mu_{\text{SP}} Q}{(u_1 \mu_{\text{SR}} \mu_{\text{SP}} N_0 + u_2 \mu_{\text{SD}} \mu_{\text{SP}} N_0 (k+r) + \mu_{\text{SD}} \mu_{\text{SR}} Q)} \right] \\
& + \sum_{k=N}^{M} \binom{M}{k} \left(\sum_{a=0}^{M-k} (-1)^a \binom{M-k}{a} \right. \\
& \left[\left(\frac{1}{\frac{u_2 N_0 (k+a)}{Q \mu_{\text{SR}}} + \frac{1}{\mu_{\text{SP}}}} \right) - \left(\frac{1}{\frac{1}{Q} \left(\frac{u_1 N_0}{\mu_{\text{SD}}} + \frac{u_2 N_0 (k+a)}{\mu_{\text{SR}}} \right) + \frac{1}{\mu_{\text{SP}}}} \right) \right] \\
& - \sum_{n=1}^{N} \sum_{\substack{m=0 \\ m+n>1}}^{k-n+1} (-1)^m \binom{k}{n-1} \binom{k-n+1}{m} \\
& \left(\frac{1}{\mu_{\text{SP}} \mu_{\text{RP}}} \right) \left(\frac{\frac{Q \mu_{\text{RD}}}{N_0}}{\frac{Q \mu_{\text{SD}}}{N_0} (m+n-1)} \right) \sum_{b=0}^{1} (-1)^b \binom{1}{b} \sum_{a=0}^{M-k} (-1)^a \\
& \binom{M-k}{a} \left(\frac{1}{\left(\frac{u_1 \frac{Q \mu_{\text{SR}}}{N_0} b \mu_{\text{SP}} + u_2 \frac{Q \mu_{\text{SD}}}{N_0} (k+a) \mu_{SP} + \frac{Q \mu_{SD}}{N_0} \frac{Q \mu_{\text{SR}}}{N_0}}{\frac{Q \mu_{\text{SD}}}{N_0} \frac{Q \mu_{\text{SR}}}{N_0} \mu_{\text{SP}}} + \frac{(u_2 - u_1 b)(m+n-1) \mu_{\text{RP}} + \frac{Q \mu_{\text{RD}}}{N_0}}{\frac{Q \mu_{\text{SD}}}{N_0} \mu_{\text{RP}} (m+n-1)} \right)^2} \right. \\
& \left[\ln \left(\frac{\frac{u_1 \frac{Q \mu_{\text{SR}}}{N_0} b \mu_{\text{SP}} + u_2 \frac{Q \mu_{\text{SD}}}{N_0} (k+a) \mu_{\text{SP}} + \frac{Q \mu_{\text{SD}}}{N_0} \frac{Q \mu_{\text{SR}}}{N_0}}{\frac{Q \mu_{\text{SD}}}{N_0} \frac{Q \mu_{\text{SR}}}{N_0} \mu_{\text{SP}}} + \frac{(u_2 - u_1 b)(m+n-1) \mu_{\text{RP}} + \frac{Q \mu_{RD}}{N_0}}{\frac{Q \mu_{SD}}{N_0} \mu_{\text{RP}} (m+n-1)}}{\frac{(u_2 - u_1 b)(m+n-1) \mu_{\text{RP}} + \frac{Q \mu_{\text{RD}}}{N_0}}{\frac{Q \mu_{\text{SD}}}{N_0} \mu_{\text{RP}} (m+n-1)}} - 1 \right) \right. \\
& \left. \left. \left. - \frac{\frac{u_1 \frac{Q \mu_{\text{SR}}}{N_0} b \mu_{\text{SP}} + u_2 \frac{Q \mu_{\text{SD}}}{N_0} (k+a) \mu_{\text{SP}} + \frac{Q \mu_{\text{SD}}}{N_0} \frac{Q \mu_{\text{SR}}}{N_0}}{\frac{Q \mu_{\text{SD}}}{N_0} \frac{Q \mu_{\text{SR}}}{N_0} \mu_{\text{SP}}} + \frac{(u_2 - u_1 b)(m+n-1) \mu_{\text{RP}} + \frac{Q \mu_{\text{RD}}}{N_0}}{\frac{Q \mu_{\text{SD}}}{N_0} \mu_{\text{RP}} (m+n-1)}}{\frac{u_1 \frac{Q \mu_{\text{SR}}}{N_0} b \mu_{\text{SP}} + u_2 \frac{Q \mu_{\text{SD}}}{N_0} (k+a) \mu_{\text{SP}} + \frac{Q \mu_{\text{SD}}}{N_0} \frac{Q \mu_{\text{SR}}}{N_0}}{\frac{Q \mu_{\text{SD}}}{N_0} \frac{Q \mu_{\text{SR}}}{N_0} \mu_{\text{SP}}}} \right] \right) \right)
\end{aligned}
\tag{4.34}
$$

4.4 Results and Discussion

In this section, we present our findings on the outage probability of the cognitive radio decode-and-forward network with incremental relaying and N^{th} best selection. We present Monte Carlo simulations to verify the exact expressions derived in this paper. For simulation purpose, we assume that the distance from the secondary source to the secondary destination, from the secondary source to the i^{th} secondary relay and from the i^{th} secondary relay to secondary destination $\forall i$ to be unity, i.e., $d_{\text{SD}} = d_{\text{SR}} = d_{\text{RD}} = 1$. We also assume that the distance from the secondary source to the primary user and from the i^{th} secondary relay to the primary user to be unity. The results are illustrated for $\alpha = 4$, where α is the pathloss exponent.

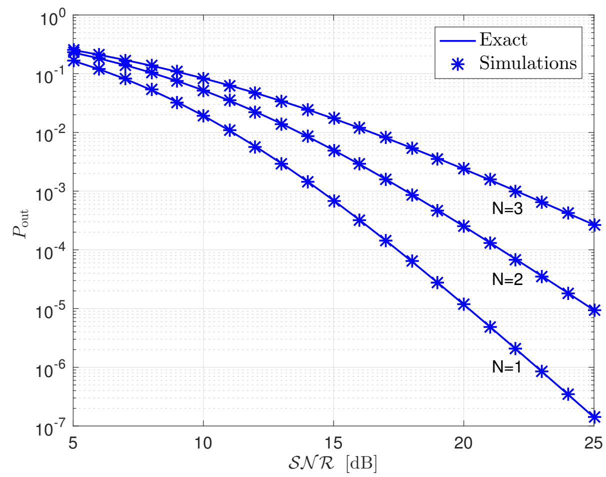

Figure 4.2. Outage probability vs SNR for M=3, and N=1,2,3.

In Fig. 5.2, we compare the performance of the system at different values of N while fixing the total number of relays at 3, and the interference threshold, Q, equal to 1. As expected, the outage probability increases with increasing the order of the selected relay. This is because the performance of the second hop (from relays to destination) worsens with the increase of the order of selected relay. This observation can provide us with a guideline to optimize the selection of the N^{th} best relay depending on the target outage and the operating SNR.

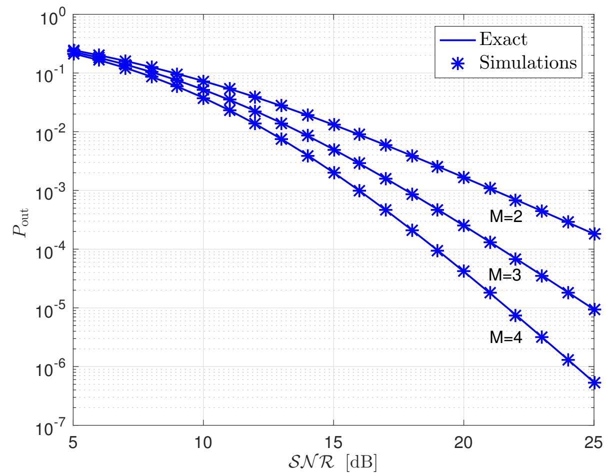

Figure 4.3. Outage probability vs SNR for N=2, and M=2,3,4.

In Fig. 5.3, we compare the outage performance of the system with changing the total number of relays while fixing the order of the selected relay. It is clear that the performance of the system improves with increasing the number of relays, as the spatial diversity improves with the increase in the number of relays and consequently the outage probability is reduced. Interestingly, the interference inflicted to the primary network does not increase with the increase in the number of secondary relays as only one relay, i.e. the N^{th} best relay, participates in the retransmission of the source message to the destination.

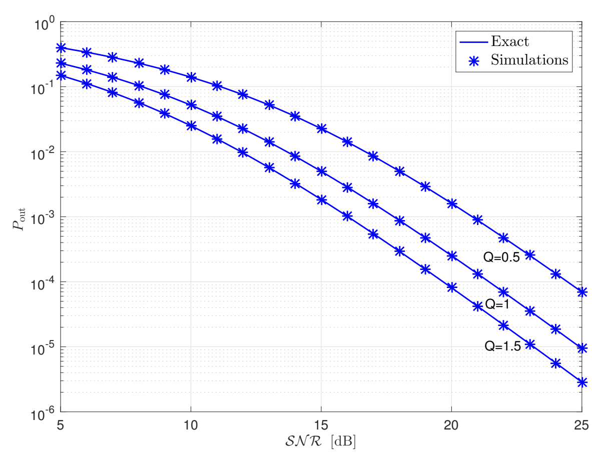

Figure 4.4. Outage probability vs SNR for N=2, and M=3 with Q=0.5,1,1.5.

In Fig. 4.4, we study the performance of the system at different values of the interference threshold Q while fixing the total number of relays and the order of the selected relay. As the figure illustrates, the outage probability decreases with increasing the maximum interference threshold as this allows the nodes to transmit at higher power.

4.5 Conclusion

In this chapter, we studied the outage performance of a generalized cooperative scheme called GCSS that is adopted for CM2M communications. The scheme is able to provide cognitive spectrum access in dense network using intermediate nodes based on general selection criterion. The performance of the cognitive scheme is evaluated by deriving the exact outage probability of the GCSS scheme that uses incremental decode-and-forward relaying which is effective in increasing the spectral efficiency and robustness of secondary spectrum sharing networks. We studied the effect of various system parameters on the outage performance such as the order of the selected relay, the total number of relays, and the interference threshold.

CHAPTER 5

Asymptotic Analysis of the GCSS Scheme for IoT Systems

5.1 Introduction

The increasing demand for high-data rate wireless transmission creates a challenge of utilizing the radio spectrum in an efficient way. The inefficient use of the radio spectrum today arises from the problem of white-space spectrum where a lot of the spectrum assigned is underutilized. One possible solution is the use of dynamic spectrum access (DSA). Cognitive radio (CR) is an enabling technology for DSA that provides unlicensed users, called secondary users (SUs), with the capability of sharing the licensed spectrum with licensed users, called primary users (PUs), in an opportunistic manner Mitola and Maguire (1999). There are three paradigms of cognitive radio networks; interweave, overlay, and underlay, in this paper, we consider the underlay mode. In underlay Cognitive radio networks the secondary transmitters have to adapt their transmission power so that the interference incurred at the primary user is below a maximum allowable interference threshold. This constraint on the transmission power degrades the performance of the secondary network deployed in fading environments Lee et al. (2011); Guo et al. (2010); Zou et al. (2010); Ding et al. (2011); Si et al. (2011); Yan et al. (2011); Xu et al. (2012).

Cooperative diversity has been proposed to combat channel fading, enhance the throughput and increase the coverage of wireless networks Laneman et al. (2004). The relays in the cooperative diversity networks have to transmit on non-overlapping time slots which reduces the spectral efficiency. The authors in Beaulieu and Hu (2006) Introduced the idea of using only a subset of the relays, called decoding set, that contains the relays that can succesfully decode the source message, those relays only will participate in retransmitting the soucre message to the destination. The authors in Bletsas et al. (2007) introduced opportunistic relay selection (ORS), also called best-relay selection, to overcome the problem of spectral efficiency.

Cognitive relay networks have received a lot of attention from researchers because of the benefits of using cooperative relays in enhancing the performance of cognitive radio networks. In Lee et al. (2011), the authors evaluated the outage probability of a cognitive relay network where the relay is selected among a set of relays based on the max-min criterion, while the best relay was selected from a set of relays that were capable of decoding the source message in Guo et al. (2010). In Zou et al. (2010) the relay selection scheme is based on the statistics of the second hop. Yan et al. in Yan et al. (2011) derived the exact outage probability for a cognitive DF relay network where a maximum power constraint was considered.

The best-relay selection scheme is an ideal protocol that achieves better performance compared to conventional cooperative communications, but in practice the best relay might not be available due to many reasons including: scheduling, load balancing, in this case, the second best relay or more generally the N^{th} best relay might be selected. The study of the N^{th} best-relay is also needed in evaluating the loss in performance due to an error in selecting the best relay that can be cause by imperfect channel state information (CSI) feedback or in the case of outdated channel information (OCI) where the relay that was the best relay at the time of selection was not the best at the transmission time instantSalhab and Zummo (2015). It is obvious that the best-relay selection scheme is a special case of the N^{th} best-relay selection scheme. The performance N^{th} best relay selection scheme in cooperative diversity networks without spectrum sharing was studied in Ikki and Ahmed (2009c, 2010a).

Cognitive relay networks employing the N^{th} best-relay selection scheme were studied in Zhang et al. (2013); Salhab and Zummo (2015).

The spectral efficiency of cooperative diversity networks can be further improved by using incremental relaying in which relaying is limited to the case where the direct transmission fails only Laneman et al. (2004). The performance of incremental amplify-and-forward relaying and incremental decode-and-forward relaying was studied in Hwang et al. (2009); Ikki and Ahmed (2011).

Considering the improvement in spectral efficiency that can be offered from using incremental opportunistic relaying, the performance of cognitive relay networks implementing incremental relaying has been studied in literature Bao and Bac (2011); Bao et al. (2011); Tourki et al. (2013); Huang et al. (2013).

In this chapter we will find the asymptotic expression for the outage probability of the underlay cognitive incremental decode-and-forward system with N^{th} best relay selection.

5.2 System Model

Consider a CM2M network that is designed to access the licensed spectrum of a primary network without affecting its performance. The CM2M network consists of a transmitting machine that is introduced as a secondary source (SS), a receiver that is known as a secondary destination (SD), and a cluster of M available relaying machines that can be used to forward the information to the SD if needed, as shown in Fig. 6.1. The CM2M network needs to restrict its activity in order not to affect the reception quality at the primary receiver (PR). On the other hand, we assume that the primary source is located far from the SD and relaying machine, thus the interference from the primary network can be neglected. The secondary CM2M network uses incremental decode-and-forward relaying strategy with a generalized-order relay selection based on SNR. Based on the adopted strategy, the SS attempts initially to deliver the required information without the help of the relaying machines. If the information can not be delivered successfully using the direct transmission, the SS will seek the help of one of the relaying machines. The candidate relay is selected from the successful detection set (D) to forward the source message in the second transmission phase. The selection of the N^{th} best relay can be done either in a centralized node

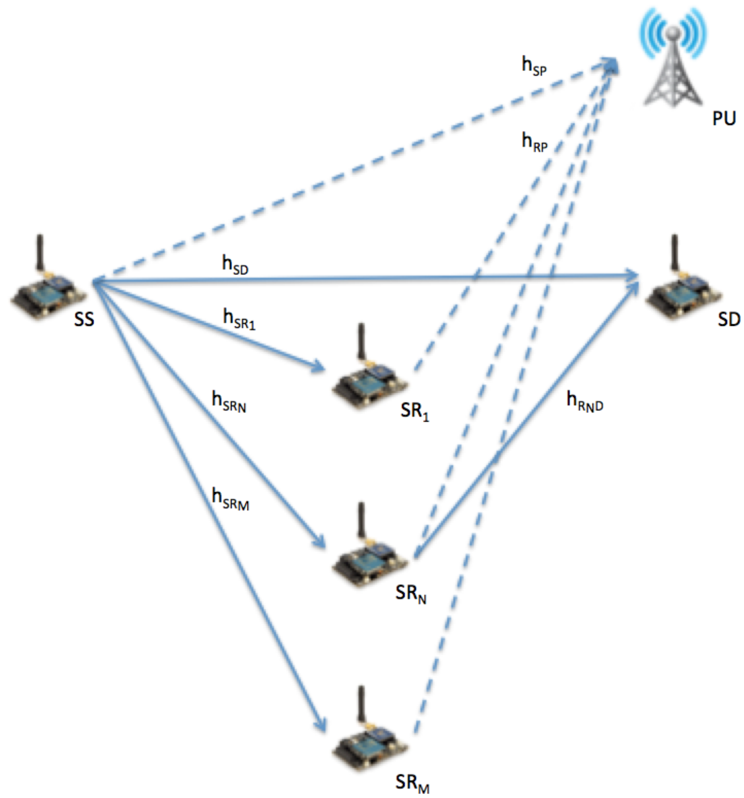

Figure 5.1. System model for the GCSS Scheme in a CM2M network.

or in a distributed manner using timers as described in Bletsas et al. (2007). The selected relaying machine is not necessary the one that improves the end-to-end signal-to-noise ratio (SNR), thus we assume a general N^{th} best relaying machine. The criterion of selecting the relay in such dynamic dense network is expected to change according to different conditions. Therefore, the generalized N^{th} best relaying strategy represent a worst performance limit.

In our system, We assume flat fading channels that are modelled as a zero mean complex Gaussian random variables. We denote the channel between the SS and SD as h_{SD}, the channel between the SS and the i^{th} relay is defined as h_{SR_i} while the channel between the i^{th} secondary relay and the SD is denoted as $h_{\text{R}_\text{i}\text{D}}$. As for the interference channel between the SS and the selected relay to the PR, they are defined as h_{SP} and h_{RP} respectively. Moreover, we have $\mathbb{E}\left[|h_{\text{SD}}|^2\right] \propto [d_{\text{SD}}^{-\alpha}]$, $\mathbb{E}\left[|h_{\text{SR}_\text{i}}|^2\right] \propto [d_{\text{SR}_\text{i}}^{-\alpha}]$, $\mathbb{E}\left[|h_{\text{R}_\text{i}\text{D}}|^2\right] \propto [d_{\text{R}_\text{i}\text{D}}^{-\alpha}]$, $\mathbb{E}\left[|h_{\text{SP}}|^2\right] \propto [d_{\text{SP}}^{-\alpha}]$, $\mathbb{E}\left[|h_{\text{RP}}|^2\right] \propto [d_{\text{RP}}^{-\alpha}]$, where d_{ij} is the distance between nodes i and j, α is the path loss exponent, and $\mathbb{E}[.]$ is the statistical average. As a result of having a cluster of relays, the relays are assumed to be close to each other so $d_{\mathrm{SR}_i} = d_{\mathrm{SR}}$ and $d_{\mathrm{R}_i\mathrm{D}} = d_{\mathrm{RD}}$ and thus the channels between the SS and the relays, and the channels between the relays and the SD are independent and identically distributed (iid). The proposed CM2M needs a limited feedback channel that acknowledge the SS and relays with the success or failure of the direct transmission, therefore, we assume a robust feedback channels between the aforementioned nodes.

The CM2M operates using underlay spectrum sharing paradigm where the secondary and primary networks transmit simultaneously on the same spectrum. The transmission power of the secondary nodes has to be adjusted so that the interference at the primary receiver is kept below a peak interference threshold Q. Thus, the maximum transmit power of the SS is given by

$$P_{\mathrm{S}} = \frac{Q}{|h_{\mathrm{SP}}|^2}. \tag{5.1}$$

Similarly, the transmit power of the secondary relay can be written as

$$P_{\mathrm{R}} = \frac{Q}{|h_{\mathrm{RP}}|^2}. \tag{5.2}$$

After the first transmission phase, the transmitted signal with power P_{S} is received at the destination as,

$$y_{\mathrm{SD}} = \sqrt{P_{\mathrm{S}}} h_{\mathrm{SD}} x + n_{\mathrm{SD}}, \tag{5.3}$$

where x is the signal transmitted by the SS and n_{SD} is complex additive white Gaussian noise (AWGN) with zero mean and variance N_0, i.e., $n_{\mathrm{SD}} \sim \mathcal{CN}(0, N_0)$. As for the received signal at the relay is given as

$$y_{\mathrm{SR}_i} = \sqrt{P_{\mathrm{S}}} h_{\mathrm{SR}_i} x + n_{\mathrm{SR}_i} \tag{5.4}$$

where $n_{\mathrm{SR}_i} \sim \mathcal{CN}(0, N_0)$ is the noise at the i^{th} relay.

If the destination decodes the source's message correctly, the destination will broadcast a feedback indicating the success of the transmission. Then, the SS can then broadcast the subsequent message in the next transmission phase. Otherwise, if the SNR of the direct link between the SS and the SD falls below the decoding threshold, the SD will broadcast a feedback indicating the failure of the transmission and announce the need of retransmission. As a result, the relay with the N^{th} best SNR on the relay-destination link is selected to forward the message to the destination in the second transmission phase. It is worth to mention that the retransmission is possible if at least one relay could decode the source message successfully, otherwise we have an outage. Moreover, N can not be greater than the number of the relays in the decoding set, outage is reported. The signal received at the SD from the cooperative transmission in the second transmission phase is given as

$$y_{\mathrm{R}_i\mathrm{D}} = \sqrt{P_{\mathrm{R}}} h_{\mathrm{R}_i\mathrm{D}} x + n_{\mathrm{R}_i\mathrm{D}} \tag{5.5}$$

where $n_{\mathrm{R}_i\mathrm{D}} \sim \mathcal{CN}(0, N_0)$ is the noise at the SD. The destination then combines both copies, y_{SD} received from the SS after the first transmission phase and $y_{\mathrm{R}_i\mathrm{D}}$ received from the N^{th} best relay in the second transmission phase using maximal ratio combining (MRC) technique.

The SNRs of the source-destination, source-relay, relay-destination links denoted as $\gamma_{\mathrm{SD}}, \gamma_{\mathrm{SR}}$, and γ_{RD} are given as

$$\begin{aligned} \gamma_{\mathrm{SD}} &= \frac{P_{\mathrm{S}} |h_{\mathrm{SD}}|^2}{N_0} \\ \gamma_{\mathrm{SR}} &= \frac{P_{\mathrm{S}} |h_{\mathrm{SR}}|^2}{N_0} \\ \gamma_{\mathrm{RD}} &= \frac{P_{\mathrm{R}} |h_{\mathrm{RD}}|^2}{N_0} \end{aligned} \tag{5.6}$$

It is clear that the SNRs are functions of P_{S} and P_{R} which are random variables. In our analysis we will start by formulating the outage probability conditioned on P_S and P_R then will take the expectation on them to complete our analysis.

5.3 Performance Analysis

Outage takes place in incremental cooperative relaying when the instantaneous rate of the system falls below a predefined spectral efficiency threshold $\mathcal{R}_{\mathcal{S}}$ in bits per second per hertz. In other words, outage occurs when the total SNR at the secondary destination from both the direct and the indirect transmissions falls below the threshold SNR which is required for successful decoding.

To evaluate the outage probability we study the behavior of the decoding set D_k first. The case when none of the M relays was able to successfully decode the source message in the first time slot leaving the decoding set empty is given as

$$\begin{aligned}\Pr(D = \emptyset | P_S) &= \Pr\left[\frac{1}{2}\log\left(1 + \gamma_{SR_i}\right) < R_S\right] \\ &= \left(1 - e^{-\frac{u_2 N_0}{\mu_{SR} P_S}}\right)^M \end{aligned} \tag{5.7}$$

where $u_2 = 2^{2\mathcal{R}_S} - 1$, and assuming i.i.d. Rayleigh fading channels.

The probability of the second case when k out of the M relays are able to successfully decode the source message in the first time slot is given as follows

$$\begin{aligned}&\Pr\left(D = D_k | P_S\right) = \Pr\Bigg[\tfrac{1}{2}\log\left(1 + \frac{P_S\left|h_{SR_i}\right|^2}{N_0}\right) \geq R_S, \forall i \in D_k, \\ &\tfrac{1}{2}\log\left(1 + \frac{P_S\left|h_{SR_j}\right|^2}{N_0}\right) < R_S, \forall j \in \overline{D}_k\Bigg] \\ &= \left(e^{-\frac{u_2 N_0}{\mu_{SR} P_S}}\right)^k \left(1 - e^{-\frac{u_2 N_0}{\mu_{SR} P_S}}\right)^{M-k} \end{aligned} \tag{5.8}$$

If the destination signals a need for retransmission then the relay with N^{th} best SNR on the link between itself and the destination is selected to retransmit the source message in the second time slot.

The outage event in this case occurs in two cases:

Case I $(0 \leq l < N)$: In this case the decoding set is either empty or the number of relays in the decoding set is smaller than the order of the selected relay N, that means that none of the relays will forward the source message and therefore the total SNR at the destination is equal to γ_{SD} given in eq. (6.4), and the outage probability is given as

$$\begin{aligned} \Pr\left(out|\, D = l, P_S \right) &= \Pr\left[\log\left(1 + \frac{P_S |h_{SD}|^2}{N_0} \right) < R_S \right] \\ &= 1 - e^{-\frac{u_1 N_0}{\mu_{SD} P_S}} \end{aligned} \tag{5.9}$$

where $u_1 = 2^{R_S} - 1$.

Case II $(N \leq K \leq M)$: In this case the number of relays in the decoding set is at least equal to the order of selection N but outage event occurs when the total instantaneous rate at the secondary destination combined from transmissions on both links, direct and relay, falls below a defined threshold. The outage probability can be represented as follows

$$\begin{aligned} & P\left(out|\, D = D_k, P_S, P_R \right) \\ &= \Pr\left[\log\left(1 + \gamma_{SD} \right) < R_S, \tfrac{1}{2}\log\left(1 + \gamma_{SD} + \gamma_N \right) < R_S \right] \\ &= \Pr\left[\gamma_{SD} < u_1, \gamma_{SD} + \gamma_N < u_2 \right] \\ &= \int_0^{u_1} F_{\gamma_N}\left(u_2 - x \right) f_X\left(x \right) dx = \int_{1-\frac{u_1}{u_2}}^{1} F_Y\left(u_2 x' \right) f_X\left(x' \right) u_2 dx' \end{aligned} \tag{5.10}$$

where $X = \gamma_{SD}$ and $f_X\left(x \right) = \frac{1}{\lambda_{SD}} e^{-\frac{x}{\lambda_{SD}}}$, where $\lambda_{SD} = \frac{\mu_{SD} P_S}{N_0}$, and $Y = \gamma_N$, and the CDF of the N^{th} best SNR from Ikki and Ahmed (2009c) can be written as

$$\begin{aligned} F_Y(y) &= \sum_{n=1}^{N} \binom{k}{n-1} [F_{\gamma_{RD}}(y)]^{k-n+1} [1 - F_{\gamma_{RD}}(y)]^{n-1} \\ &= 1 + \sum_{n=1}^{N} \sum_{\substack{m=0 \\ n+m>1}}^{k-n+1} (-1)^m \begin{pmatrix} k \\ n-1 \end{pmatrix} \begin{pmatrix} k-n+1 \\ m \end{pmatrix} e^{-\frac{(m+n-1)y}{\lambda_{RD}}} \end{aligned} \tag{5.11}$$

where $F_{\gamma_{RD}}(y)$ is the CDF of the SNR of the relay-destination link and is given as $F_{\gamma_{RD}}(y) = 1 - e^{-\frac{y}{\lambda_{RD}}}$ where $\lambda_{RD} = \frac{P_R \mu_{RD}}{N_0}$.

By substituting eq.(6.9) into eq.(6.8) we obtain an expression for $P\left(out|\, D = D_k, P_S, P_R\right)$ which we will solve in section (6.4).

The total outage probability conditioned on P_S and P_R is then written as

$$\begin{aligned} P\left(out|\, P_S, P_R\right) &= \sum_{l=0}^{N-1} \binom{M}{l} P\left(out|\, D = D_l, P_S\right) P\left(D = D_l|\, P_S\right) \\ &+ \sum_{k=N}^{M} \binom{M}{k} P\left(out|\, D = D_k, P_S, P_R\right) P\left(D = D_k|\, P_S, P_R\right) \end{aligned} \tag{5.12}$$

5.4 Asymptotic Analysis

In this section we will derive the asymptotic expression for the outage probability of the underlay cognitive incremental decode-and-forward system with N^{th} best relay selection

In the high SNR region as $\gamma \to \infty$, so $u_1 N_0$ and $u_2 N_0 \to 0$.

To calculate P(out) we will find the expressions for the terms in eq.(6.5) as $\gamma \to \infty$,

$$P\left(D=\emptyset|\,P_S\right)=(1-e^{-\frac{u_2N_0}{\mu_{SR}P_S}})^M$$
$$\approx\left(\frac{u_2N_0}{\mu_{SR}P_S}\right)^M \tag{5.13}$$

and from eq.(4.9), we obtain

$$P\left(out|\,D=l,P_S\right)=1-e^{-\frac{u_1N_0}{\mu_{SD}P_S}}$$
$$\approx\frac{u_1N_0}{\mu_{SD}P_S} \tag{5.14}$$

As $u_2N_0\to 0$, $e^{-\frac{u_2N_0}{\mu_{SR}P_S}}\approx 1$, therefore the asymptotic expression for eq.(6.6)

$$P\left(D=D_k|P_S\right)=\left(e^{-\frac{u_2N_0}{\mu_{SR}P_S}}\right)^k\left(1-e^{-\frac{u_2N_0}{\mu_{SR}P_S}}\right)^{M-k}$$
$$\approx\left(\frac{u_2N_0}{\mu_{SR}P_S}\right)^{M-k} \tag{5.15}$$

To find the asymptotic expression for $P\left(out|\,D=D_k,P_S,P_R\right)$ we recall that from eq.(6.8) $P\left(out|\,D=D_k,P_S,P_R\right)=\int\limits_0^{u_1}F_Y\left(u_2-x\right)f_X\left(x\right)dx$, where $F_Y(y)$ is the CDF of the N^{th} best SNR and is given as

$$F_Y\left(y\right)=\sum_{n=1}^{N}\binom{k}{n-1}[F_{\gamma_{\mathrm{RD}}}(y)]^{k-n+1}[1-F_{\gamma_{\mathrm{RD}}}(y)]^{n-1}$$
$$=\sum_{n=1}^{N}\left(\begin{array}{c}k\\ \\ n-1\end{array}\right)\left(1-e^{-\frac{y}{\lambda_{\mathrm{RD}}}}\right)^{k-n+1}\left(e^{-\frac{y}{\lambda_{\mathrm{RD}}}}\right)^{n-1} \tag{5.16}$$

At high SNR the expression for $F_Y(y)$ given as

$$F_Y\left(y\right)=\sum_{n=1}^{N}\binom{k}{n-1}\left(\frac{y}{\lambda_{RD}}\right)^{k-n+1} \tag{5.17}$$

and the pdf of the SNR of the direct link $f_X(x)$ is given as

$$f_X(x) = \frac{1}{\lambda_{SD}} e^{-\frac{x}{\lambda_{SD}}} \approx \frac{1}{\lambda_{SD}} \tag{5.18}$$

The probability $P(out|\, D = D_k, P_S, P_R)$ at high SNR is given as follows

$$\begin{aligned} & P(out|\, D = D_k, P_S, P_R) \\ & = \frac{1}{\lambda_{SD}} \int_0^{u_1} \sum_{n=1}^{N} \binom{k}{n-1} \left(\frac{u_2 - x}{\lambda_{RD}} \right)^{k-n+1} dx \\ & = \frac{u_2}{\lambda_{SD}} \int_{1-\frac{u_1}{u_2}}^{1} \sum_{n=1}^{N} \binom{k}{n-1} \left(\frac{u_2 x'}{\lambda_{RD}} \right)^{k-n+1} dx' \\ & = \frac{u_2}{\lambda_{SD}} \sum_{n=1}^{N} \binom{k}{n-1} \left(\frac{u_2}{\lambda_{RD}} \right)^{k-n+1} \frac{\left(1 - \left(1 - \frac{u_1}{u_2}\right)^{k-n+2}\right)}{(k-n+2)} \end{aligned} \tag{5.19}$$

To find the asymptotic expression for the total outage probability, we take the expectation of the outage probability conditioned on P_S and P_R which is given in eq.(6.10) with respect to P_S and P_R.

$$P(out) = \sum_{l=0}^{N-1} \binom{M}{l} A_1 + \sum_{k=N}^{M} \binom{M}{k} A_2 \tag{5.20}$$

where $A_1 = E_{P_S}\left[P(out|\, D = D_l, P_S)\, P(D = D_l|\, P_S)\right]$,

and $A_2 = E_{P_S,P_R}\left[P(out|\, D = D_k, P_S, P_R)\, P(D = D_k|\, P_S, P_R)\right]$.

But first we will find the b^{th} moment of $\frac{1}{P_S}$ and $\frac{1}{P_R}$ that will be used to find the asymptotic expressions.

5.4.1 The b^{th} moment of $\frac{1}{P_S}$ and $\frac{1}{P_R}$

Setting $X = |h_{SP}|^2$ then the b^{th} moment of $\frac{1}{P_S}$ is given as

$$\begin{aligned} E\left[\left(\frac{1}{P_S}\right)^b\right] &= E\left[\left(\frac{X}{Q}\right)^b\right] \\ &= \int_0^\infty \frac{x^b}{Q^b} f_X(x)dx \\ &= \frac{1}{\mu_{SP} Q^b} \int_0^\infty x^b e^{-\frac{x}{\mu_{SP}}} dx \end{aligned} \tag{5.21}$$

let $z = \frac{x}{\mu_{SP}}$, then the b^{th} moment of $\frac{1}{P_S}$ is given as

$$\begin{aligned} E\left[\left(\frac{1}{P_S}\right)^b\right] &= \frac{{\mu_{SP}}^b}{Q^b} \int_0^\infty z^b e^{-z} dz \\ &= \frac{{\mu_{SP}}^b}{Q^b} \Gamma(b+1) \end{aligned} \tag{5.22}$$

where $\Gamma(\alpha)$ is the gamma function and is given as $\Gamma(\alpha) = \int_0^\infty t^{\alpha-1} e^{-t} dt$, using the fact that $\Gamma(\alpha) = (\alpha-1)!$ then the b^{th} moment of $\frac{1}{P_S}$ is given as

$$E\left[\left(\frac{1}{P_S}\right)^b\right] = \frac{\mu_{SP}^b b!}{Q^b} \tag{5.23}$$

Similarly, the b^{th} moment of $\frac{1}{P_R}$ is given as

$$E\left[\left(\frac{1}{P_R}\right)^b\right] = \frac{\mu_{RP}^b b!}{Q^b} \tag{5.24}$$

5.4.2 Calculating A_1

Using the expressions in equations (5.13), (5.14), and (5.23), we can find the asymptotic expression A_1 as follows

$$\begin{aligned}
A_1 &= E_{P_S}\left[P\left(out|\, D=\emptyset, P_S\right)P\left(D=\emptyset|\, P_S\right)\right] \\
&= E_{P_S}\left[\left(\frac{u_1 N_0}{\mu_{SD}P_S}\right)\left(\frac{u_2 N_0}{\mu_{SR}P_S}\right)^M\right] \\
&= \frac{u_1 u_2^M N_0^{M+1}}{\mu_{SD}\mu_{SR}^M} E_{P_S}\left[\left(\frac{1}{P_S}\right)^{M+1}\right] \\
&= \frac{u_1 u_2^M N_0^{M+1}(M+1)!}{\mu_{SD}\mu_{SR}^M \mu_{SP}^{M+1} Q^{M+1}}
\end{aligned} \tag{5.25}$$

5.4.3 Calculating A_2

Using the expressions found in equations (6.13) and (6.15), we can find A_2 as follows

$$\begin{aligned}
A_2 &= E_{P_S,P_R}\left[P\left(out|\, D=D_k, P_S, P_R\right)P\left(D=D_k|\, P_S, P_R\right)\right] \\
&= E_{P_S,P_R}\Bigg[\frac{u_2 N_0}{P_S\mu_{SD}}\sum_{n=1}^{N}\binom{k}{n-1}\left(\frac{u_2 N_0}{P_R\mu_{RD}}\right)^{k-n+1} \\
&\quad \frac{\left(1-\left(1-\frac{u_1}{u_2}\right)^{k-n+2}\right)}{(k-n+2)}\left(\frac{u_2 N_0}{P_S\mu_{SR}}\right)^{M-k}\Bigg] \\
&= \sum_{n=1}^{N}\binom{k}{n-1}\frac{(u_2 N_0)^{M-n+2}}{\mu_{SD}\mu_{SR}^{M-k}\mu_{RD}^{k-n+1}}\frac{\left(1-\left(1-\frac{u_1}{u_2}\right)^{k-n+2}\right)}{(k-n+2)} \\
&\quad E\left[\left(\frac{1}{P_S}\right)^{M-k+1}\right]E\left[\left(\frac{1}{P_R}\right)^{k-n+1}\right]
\end{aligned} \tag{5.26}$$

Using the expressions for the b^{th} moment of $\frac{1}{P_S}$ and $\frac{1}{P_R}$

$$A_2 = \sum_{n=1}^{N} \begin{pmatrix} k \\ n-1 \end{pmatrix} \frac{(M-k+1)!\,(k-n+1)!}{(k-n+2)} \frac{\mu_{SP}^{M-k+1} \mu_{RP}^{k-n+1} \left(\frac{u_2 N_0}{Q}\right)^{M-n+2} \left(1 - \left(1 - \frac{u_1}{u_2}\right)^{k-n+2}\right)}{\mu_{SD} \mu_{SR}^{M-k} \mu_{RD}^{k-n+1}} \tag{5.27}$$

5.4.4 Calculating the asymptotic expression for total outage probability ($P_{(out)}$)

To calculate the asymptotic expression for the total outage probability we substitute in eq.(5.20) with the expressions found in equations (5.25) and (5.27) as follows

$$P\,(out) = \frac{u_1 (M+1)!}{\mu_{SD}} \left(\frac{u_2}{\mu_{SR}}\right)^{M} \left(\frac{N_0}{\mu_{SP} Q}\right)^{M+1} + \sum_{k=1}^{M} \binom{M}{k} \sum_{n=1}^{N} \begin{pmatrix} k \\ n-1 \end{pmatrix} \frac{(M-k+1)!\,(k-n+1)!}{(k-n+2)} \frac{\mu_{SP}^{M-k+1} \mu_{RP}^{k-n+1} \left(\frac{u_2 N_0}{Q}\right)^{M-n+2} \left(1 - \left(1 - \frac{u_1}{u_2}\right)^{k-n+2}\right)}{\mu_{SD} \mu_{SR}^{M-k} \mu_{RD}^{k-n+1}} \tag{5.28}$$

5.5 Results and Discussion

In this section, we present our findings on the outage probability of the cognitive radio decode-and-forward network with incremental relaying and N^{th} best selection. We present Monte Carlo simulations to verify the exact expressions derived in this paper. For simulation purpose, we assume that the distance from the secondary source to the secondary destination, from the secondary source to the kth secondary relay and from the kth secondary relay to secondary destination $\forall k$ to be unity, i.e $d_{SD} = d_{SR} = d_{RD} = 1$. We also assume that the distance from the secondary source to the primary user and from the kth secondary

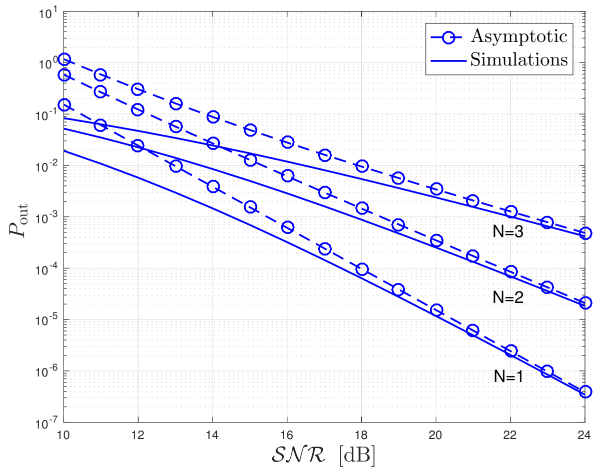

Figure 5.2. Outage probability vs SNR for M=3, and N=1,2,3.

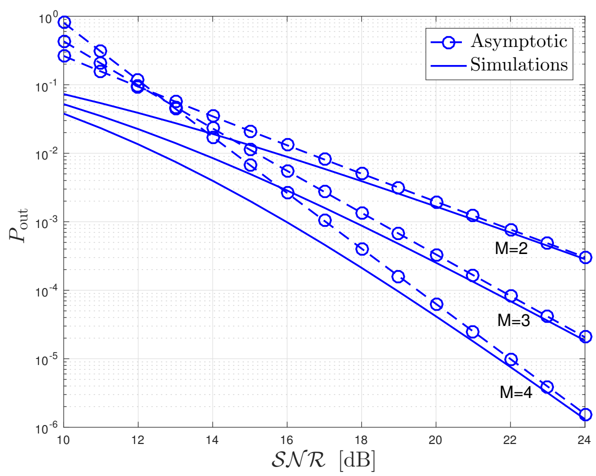

Figure 5.3. Outage probability vs SNR for N=2, and M=2,3,4.

relay to the primary user to be unity. The results are illustrated for $\alpha = 4$, where α is the pathloss exponent.

In fig.(5.2), we compare the performance of the system at different values of N while fixing the total number of relays at 3, and the interference threshold, Q, equal to 1. As observed from our results, the outage probability increases with increasing the order of the selected relay. This is because the performance of the second hop (from relays to destination) worsens with the increase of the order of selected relay. In fig.(5.3), we compare the outage performance of the system with changing the total number of relays while fixing the order of

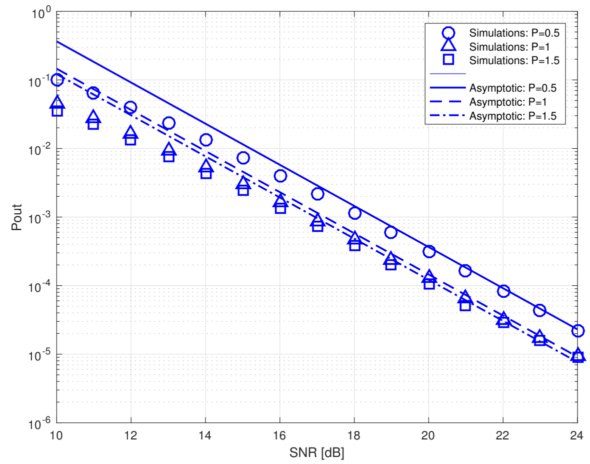

Figure 5.4. Outage probability vs SNR for N=1, and M=3 with P_m=0.5,1,1.5.

the selected relay. It is clear that the performance of the system improves with increasing the number of relays, as the spatial diversity improves with the increase in the number of relays and consequently the outage probability is reduced. In fig.(5.4), we study the performance of the system at different values of the Max Transmit Power Constraint while fixing the total number of relays and the order of the selected relay. Our results show that the outage probability decreases with increasing the maximum interference threshold as this allows the nodes to transmit at higher power, but this performance decreases with the increase of the Max Transmit Power Constraint.

5.6 Conclusion

In this paper, we studied the outage performance of a cognitive relay network utilizing incremental decode-and-forward relaying to improve the spectral efficiency of the secondary network. We studied the generalized N^{th} best relay selection scheme which is more efficient compared to opportunistic relaying in practical situations. We derived a closed form of the asymptotic outage probability of the system taking into consideration the effect of multiple primary users on the transmit power of the nodes of the secondary network. We have demonstrated the effect of the number of relays, the order of relay selection and the Max

Transmit Power Constraint on the performance of the system.

CHAPTER 6

Asymptotic Analysis of the GCSS Scheme with Multiple Primary Users and Transmit Power Threshold

6.1 Introduction

The increasing demand for high-data rate wireless transmission creates a challenge of utilizing the radio spectrum in an efficient way. The inefficient use of the radio spectrum today arises from the problem of white-space spectrum where a lot of the spectrum assigned is underutilized. One possible solution is the use of dynamic spectrum access (DSA). Cognitive radio (CR) is an enabling technology for DSA that provides unlicensed users, called secondary users (SUs), with the capability of sharing the licensed spectrum with licensed users, called primary users (PUs), in an opportunistic manner Mitola and Maguire (1999). There are three paradigms of cognitive radio networks; interweave, overlay, and underlay, in this paper, we consider the underlay mode. In underlay Cognitive radio networks the secondary transmitters have to adapt their transmission power so that the interference incurred at the primary user is below a maximum allowable interference threshold. This constraint on the transmission power degrades the performance of the secondary network deployed in fading environments Lee et al. (2011); Guo et al. (2010); Zou et al. (2010); Ding et al. (2011); Si et al. (2011); Yan et al. (2011); Xu et al. (2012).

Cooperative diversity has been proposed to combat channel fading, enhance the throughput and increase the coverage of wireless networks Laneman et al. (2004). The relays in the cooperative diversity networks have to transmit on non-overlapping time slots which reduces the spectral efficiency. The authors in Beaulieu and Hu (2006) Introduced the idea of using only a subset of the relays, called decoding set, that contains the relays that can succesfully decode the source message, those relays only will participate in retransmitting the soucre message to the destination. The authors in Bletsas et al. (2007) introduced opportunistic relay selection (ORS), also called best-relay selection, to overcome the problem of spectral efficiency.

Cognitive relay networks have received a lot of attention from researchers because of the benefits of using cooperative relays in enhancing the performance of cognitive radio networks. In Lee et al. (2011), the authors evaluated the outage probability of a cognitive relay network where the relay is selected among a set of relays based on the max-min criterion, while the best relay was selected from a set of relays that were capable of decoding the source message in Guo et al. (2010). In Zou et al. (2010) the relay selection scheme is based on the statistics of the second hop. Yan et al. in Yan et al. (2011) derived the exact outage probability for a cognitive DF relay network where a maximum power constraint was considered.

The best-relay selection scheme is an ideal protocol that achieves better performance compared to conventional cooperative communications, but in practice the best relay might not be available due to many reasons including: scheduling, load balancing, in this case, the second best relay or more generally the N^{th} best relay might be selected. The study of the N^{th} best-relay is also needed in evaluating the loss in performance due to an error in selecting the best relay that can be cause by imperfect channel state information (CSI) feedback or in the case of outdated channel information (OCI) where the relay that was the best relay at the time of selection was not the best at the transmission time instantSalhab and Zummo (2015). It is obvious that the best-relay selection scheme is a special case of the N^{th} best-relay selection scheme. The performance N^{th} best relay selection scheme in cooperative diversity networks without spectrum sharing was studied in Ikki and Ahmed (2009c, 2010a).

Cognitive relay networks employing the N^{th} best-relay selection scheme were studied in Zhang et al. (2013); Salhab and Zummo (2015).

The spectral efficiency of cooperative diversity networks can be further improved by using incremental relaying in which relaying is limited to the case where the direct transmission fails only Laneman et al. (2004). The performance of incremental amplify-and-forward relaying and incremental decode-and-forward relaying was studied in Hwang et al. (2009); Ikki and Ahmed (2011).

Considering the improvement in spectral efficiency that can be offered from using incremental opportunistic relaying, the performance of cognitive relay networks implementing incremental relaying has been studied in literature Bao and Bac (2011); Bao et al. (2011); Tourki et al. (2013); Huang et al. (2013).

6.2 System Model

Consider the cognitive relay network (CRN) shown in fig. 6.1 in which the secondary network is designed to access the spectrum of the authorized primary network without affecting its performance. The secondary network consists a secondary source (SS), a secondary destination (SD), and a cluster of M available relaying machines that can be used to forward the information to the secondary destination. Whereas the primary network consists of L primary receivers with the primary transmitter assumed to be located far from the secondary network Lee et al. (2011); Yan et al. (2011). We denote the channel between the secondary source and the secondary destination as $h_{S,D}$, and the channel between the secondary source and the i^{th} secondary relay as h_{S,R_i}, and the channel between the i^{th} secondary relay and the secondary destination as $h_{R_i,D}$, and the channel between the secondary source and the primary receiver as $h_{S,P}$, and the channel between the i^{th} secondary relay and the primary receiver as $h_{R_i,P}$. We assume that the channels in the network are modeled as i.i.d. Rayleigh fading channels with variances $\sigma^2_{S,D}$, σ^2_{S,R_i}, $\sigma^2_{R_i,D}$, $\sigma^2_{S,P}$, and $\sigma^2_{R_i,P}$ respectively. Since all channels are i.i.d, we can express h_{S,R_i} as $h_{S,R}$ and $h_{R_i,D}$ as $h_{R,D}$.

In underlay spectrum sharing networks, the secondary and primary networks transmit simultaneously on the same spectrum but the transmission power of the secondary nodes

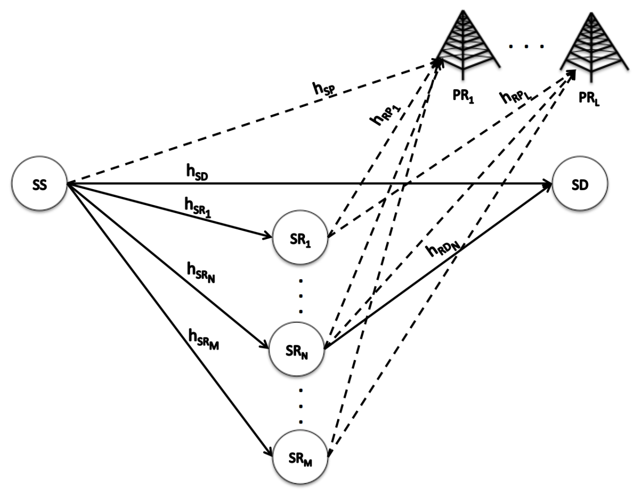

Figure 6.1. System Model for the Generalized Cooperative Spectrum Sensing Scheme in a M2M network

has to be adjusted so that the interference at the primary receiver is kept below a peak interference threshold Q. The transmission power of the source and the relays is also constrained with a maximum transmit power constrainst, P_m. Therefore the transmit power of the secondary source is written as

$$\begin{aligned} P_S &= \min\left[P_m, \min_{i=1,\ldots,L}\left(\frac{Q}{\left|h_{SP_i}\right|^2}\right)\right] \\ &= \min\left[P_m, \left(\frac{Q}{\max\left|h_{SP_i}\right|^2}\right)\right] \end{aligned} \tag{6.1}$$

Similarly, the transmit power of the secondary relay can be written as

$$P_R = \min\left[P_m, \left(\frac{Q}{\max\left|h_{RP_i}\right|^2}\right)\right] \tag{6.2}$$

In the first time slot, the secondary source broadcasts its message to the secondary relays and secondary destination with power P_S. If the destination decodes the source's message correctly, the destination will broadcast a feedback indicating the success of the transmission and the secondary source will then broadcast a fresh message in the next time slot. Otherwise, the destination will broadcast a feedback indicating the failure of the transmission and the need of retransmission. The relay with the N^{th} best SNR on the relay-destination link from the decoding set D is selected to forward the message to the destination in the second time slot. The selection criterion for our model can be written as $SR_N = \arg \ N^{th}\max_{i \in D_k} \left(\frac{P_R \left| h_{R_i D} \right|^2}{N_0} \right)$ and the instantaneous SNR of the N^{th} best relay,γ_N , is given as

$$\gamma_N = N^{th}\max_{i \in D_k} \left(\frac{P_R \left| h_{R_i D} \right|^2}{N_0} \right) \tag{6.3}$$

.Thus, the retransmission is possible if at least one relay could decode the source message successfully, otherwise we have an outage. The order of the selected relay can not be greater than the number of the relays in the decoding set, otherwise we have an outage. The destination then combines both copies of the source message using Maximal Ratio Combining (MRC). The SNRs of the source-destination, source-relay, relay-destination links denoted as $\gamma_{SD}, \gamma_{SR}, \ and \ \gamma_{RD}$ are given as

$$\gamma_{SD} = \frac{P_S |h_{SD}|^2}{N_0}$$
$$\gamma_{SR} = \frac{P_S |h_{SR}|^2}{N_0}$$
$$\gamma_{RD} = \frac{P_R |h_{RD}|^2}{N_0} \tag{6.4}$$

It is clear that the SNRs are functions of P_S and P_R which are random variables. In our analysis we will start by formulating the outage probability conditioned on P_S and P_R then will take the expectation on them to complete our analysis.

6.3 Performance Analysis

Outage takes place in incremental cooperative relaying when the instantaneous rate of the system falls below a predefined spectral efficiency threshold $\mathcal{R}_S$ in bits per second per hertz. In other words, outage occurs when the total SNR at the secondary destination from both the direct and the indirect transmissions falls below the threshold SNR which is required for successful decoding.

To evaluate the outage probability we study the behavior of the decoding set D_k first. The case when none of the M relays was able to successfully decode the source message in the first time slot leaving the decoding set empty is given as

$$\begin{aligned}\Pr(D = \emptyset | P_S) &= \Pr\left[\frac{1}{2}\log\left(1 + \gamma_{SR_i}\right) < R_S\right] \\ &= \left(1 - e^{-\frac{u_2 N_0}{\mu_{SR} P_S}}\right)^M \end{aligned} \tag{6.5}$$

where $u_2 = 2^{2\mathcal{R}_S} - 1$, and assuming i.i.d. Rayleigh fading channels.

The probability of the second case when k out of the M relays are able to successfully decode the source message in the first time slot is given as follows

$$\begin{aligned}&\Pr\left(D = D_k | P_S\right) = \Pr\Bigg[\tfrac{1}{2}\log\left(1 + \frac{P_S \left|h_{SR_i}\right|^2}{N_0}\right) \geq R_S, \forall i \in D_k, \\ &\tfrac{1}{2}\log\left(1 + \frac{P_S \left|h_{SR_j}\right|^2}{N_0}\right) < R_S, \forall j \in \overline{D}_k\Bigg] \\ &= \left(e^{-\frac{u_2 N_0}{\mu_{SR} P_S}}\right)^k \left(1 - e^{-\frac{u_2 N_0}{\mu_{SR} P_S}}\right)^{M-k} \end{aligned} \tag{6.6}$$

If the destination signals a need for retransmission then the relay with N^{th} best SNR on the link between itself and the destination is selected to retransmit the source message in the second time slot.

The outage event in this case occurs in two cases:

Case I $(0 \leq l < N)$: In this case the decoding set is either empty or the number of relays in the decoding set is smaller than the order of the selected relay N, that means that none of the relays will forward the source message and therefore the total SNR at the destination is equal to γ_{SD} given in eq. (6.4), and the outage probability is given as

$$\begin{aligned} \Pr\left(out\middle|\, D = l, P_S\right) &= \Pr\left[\log\left(1 + \frac{P_S|h_{SD}|^2}{N_0}\right) < R_S\right] \\ &= 1 - e^{-\frac{u_1 N_0}{\mu_{SD} P_S}} \end{aligned} \tag{6.7}$$

where $u_1 = 2^{R_S} - 1$.

Case II $(N \leq K \leq M)$: In this case the number of relays in the decoding set is at least equal to the order of selection N but outage event occurs when the total instantaneous rate at the secondary destination combined from transmissions on both links, direct and relay, falls below a defined threshold. The outage probability can be represented as follows

$$\begin{aligned} &P\left(out\middle|\, D = D_k, P_S, P_R\right) \\ &= \Pr\left[\log\left(1 + \gamma_{SD}\right) < R_S, \tfrac{1}{2}\log\left(1 + \gamma_{SD} + \gamma_N\right) < R_S\right] \\ &= \Pr\left[\gamma_{SD} < u_1, \gamma_{SD} + \gamma_N < u_2\right] \\ &= \int_0^{u_1} F_{\gamma_N}\left(u_2 - x\right) f_X\left(x\right) dx = \int_{1-\frac{u_1}{u_2}}^{1} F_Y\left(u_2 x'\right) f_X\left(x'\right) u_2 dx' \end{aligned} \tag{6.8}$$

where $X = \gamma_{SD}$ and $f_X\left(x\right) = \frac{1}{\lambda_{SD}} e^{-\frac{x}{\lambda_{SD}}}$, where $\lambda_{SD} = \frac{\mu_{SD} P_S}{N_0}$, and $Y = \gamma_N$, and the CDF of the N^{th} best SNR from Ikki and Ahmed (2009c) can be written as

$$F_Y(y) = \sum_{n=1}^{N} \binom{k}{n-1} [F_{\gamma_{RD}}(y)]^{k-n+1} [1 - F_{\gamma_{RD}}(y)]^{n-1}$$
$$= 1 + \sum_{n=1}^{N} \sum_{\substack{m=0 \\ n+m>1}}^{k-n+1} (-1)^m \begin{pmatrix} k \\ \\ n-1 \end{pmatrix} \begin{pmatrix} k-n+1 \\ \\ m \end{pmatrix} e^{-\frac{(m+n-1)y}{\lambda_{RD}}} \tag{6.9}$$

where $F_{\gamma_{RD}}(y)$ is the CDF of the SNR of the relay-destination link and is given as $F_{\gamma_{RD}}(y) = 1 - e^{-\frac{y}{\lambda_{RD}}}$ where $\lambda_{RD} = \frac{P_R \mu_{RD}}{N_0}$.

By substituting eq.(6.9) into eq.(6.8) we obtain an expression for $P\left(out\right| D = D_k, P_S, P_R)$ which we will solve in section (6.4).

The total outage probability conditioned on P_S and P_R is then written as

$$\begin{aligned} P\left(out\right| P_S, P_R) &= \sum_{l=0}^{N-1} \binom{M}{l} P\left(out\right| D = D_l, P_S) P\left(D = D_l\right| P_S) \\ &+ \sum_{k=N}^{M} \binom{M}{k} P\left(out\right| D = D_k, P_S, P_R) P\left(D = D_k\right| P_S, P_R) \end{aligned} \tag{6.10}$$

6.4 Asymptotic Analysis

In this section we will derive the asymptotic expression for the outage probability of the underlay cognitive incremental decode-and-forward system with N^{th} best relay selection with a Primary network consisting of multiple primary users (PUs).

In the high SNR region as $\gamma \to \infty$, so $u_1 N_0$ and $u_2 N_0 \to 0$. To calculate the outage probability we will have to find the expressions for the terms in eq.(6.10) as $\gamma \to \infty$,

$$P\left(D = \emptyset\right| P_S) \approx \left(\frac{u_2 N_0}{\mu_{SR} P_S}\right)^M \tag{6.11}$$

and from eq.(6.7), we obtain

$$P\left(out|\, D = l, P_S\right) \approx \tfrac{u_1 N_0}{\mu_{SD} P_S} \tag{6.12}$$

As $u_2 N_0 \to 0$, $e^{-\frac{u_2 N_0}{\mu_{SR} P_S}} \approx 1$, therefore the asymptotic expression for eq.(6.6)

$$P\left(D = D_k|P_S\right) \approx \left(\tfrac{u_2 N_0}{\mu_{SR} P_S}\right)^{M-k} \tag{6.13}$$

To find the asymptotic expression for $P\left(out|\, D = D_k, P_S, P_R\right)$ we recall from eq.(6.8) that $P\left(out|\, D = D_k, P_S, P_R\right) = \int\limits_0^{u_1} F_Y\left(u_2 - x\right) f_X\left(x\right) dx$. At high SNR, the expression for $F_Y(y)$ given in eq.(6.9) can be written as

$$F_Y\left(y\right) = \sum_{n=1}^{N} \binom{k}{n-1} \left(\frac{y}{\lambda_{RD}}\right)^{k-n+1} \tag{6.14}$$

and the pdf of the SNR of the direct link $f_X\left(x\right)$ is given as $f_X\left(x\right) = \frac{1}{\lambda_{SD}} e^{-\frac{x}{\lambda_{SD}}} \approx \frac{1}{\lambda_{SD}}$. The probability $P\left(out|\, D = D_k, P_S, P_R\right)$ at high SNR is given as follows

$$\begin{aligned} &P\left(out|\, D = D_k, P_S, P_R\right) \\ &= \frac{u_2}{\lambda_{SD}} \int\limits_{1-\frac{u_1}{u_2}}^{1} \sum_{n=1}^{N} \binom{k}{n-1} \left(\frac{u_2 x'}{\lambda_{RD}}\right)^{k-n+1} dx' \\ &= \frac{u_2}{\lambda_{SD}} \sum_{n=1}^{N} \binom{k}{n-1} \left(\frac{u_2}{\lambda_{RD}}\right)^{k-n+1} \frac{\left(1 - \left(1 - \frac{u_1}{u_2}\right)^{k-n+2}\right)}{\left(k-n+2\right)} \end{aligned} \tag{6.15}$$

To find the asymptotic expression for the total outage probability, we take the expectation of the outage probability conditioned on P_S and P_R which is given in eq.(6.10) with respect to P_S and P_R. $P\left(out\right) = \sum\limits_{l=0}^{N-1} \binom{M}{l} A_1 + \sum\limits_{k=N}^{M} \binom{M}{k} A_2$.

Where $A_1 = E_{P_S}\left[P\left(out\middle| D = D_l, P_S\right)P\left(D = D_l\middle| P_S\right)\right]$,

and $A_2 = E_{P_S,P_R}\left[P\left(out\middle| D = D_k, P_S, P_R\right)P\left(D = D_k\middle| P_S, P_R\right)\right]$.

But first we will find the b^{th} moment of $\frac{1}{P_S}$ and $\frac{1}{P_R}$ that will be used to find the asymptotic expressions.

Setting $X_S = \max\limits_{i=1,\ldots,L} \left|h_{SP_i}\right|^2$, with CDF given as follows

$$\begin{aligned} F_{X_S}\left(x\right) &= \Pr\left[\max_{i=1,\ldots,L} \left|h_{SP_i}\right|^2 \le x\right] \\ &= \left(1 - e^{-\frac{x}{\mu_{SP}}}\right)^L \\ &= 1 + \sum_{r=1}^{L} \left(-1\right)^r \binom{L}{r} e^{-\frac{r}{\mu_{SP}}x} \end{aligned} \tag{6.16}$$

from which we can find the PDF of X_S by differentiating with respect to x, and the PDF is this given as

$$f_{X_S}(x) = \sum_{r=1}^{L} \left(-1\right)^{r+1} \binom{L}{r} \frac{r}{\mu_{SP}} e^{-\frac{r}{\mu_{SP}}x} \tag{6.17}$$

The b^{th} moment of $\frac{1}{P_S}$ is given as

$$\begin{aligned} E\left[\left(\frac{1}{P_S}\right)^b\right] &= \left(\frac{1}{P_m}\right)^b \int_0^{\frac{Q}{P_m}} f_{X_S}(x)dx + \int_{\frac{Q}{P_m}}^{\infty} \frac{x^b}{Q^b} f_{X_S}(x)dx \\ &= \frac{\left(1 - e^{-\frac{Q}{\mu_{SP}P_m}}\right)^L}{{P_m}^b} + I_a \end{aligned} \tag{6.18}$$

To solve I_a, let $z = \frac{r}{\mu_{SP}} x$, then I_a can be written as

$$I_a = \sum_{r=1}^{L} (-1)^{r+1} \binom{L}{r} \left(\frac{\mu_{SP}}{rQ}\right)^b \int\limits_{\frac{rQ}{\mu_{SP} P_m}}^{\infty} z^b e^{-z} dz$$
$$= \sum_{r=1}^{L} (-1)^{r+1} \binom{L}{r} \left(\frac{\mu_{SP}}{rQ}\right)^b \Gamma\left(b+1, \frac{rQ}{\mu_{SP} P_m}\right) \tag{6.19}$$

where $\Gamma(.,.)$ represents the upper incomplete Gamma function.

The b^{th} moment of $\frac{1}{P_S}$ can thus be given as

$$E\left[\left(\frac{1}{P_S}\right)^b\right] = \frac{\left(1 - e^{-\frac{Q}{\mu_{SP} P_m}}\right)^L}{{P_m}^b} + \sum_{r=1}^{L} (-1)^{r+1} \binom{L}{r} \left(\frac{\mu_{SP}}{rQ}\right)^b \Gamma\left(b+1, \frac{rQ}{\mu_{SP} P_m}\right) \tag{6.20}$$

Similarly, the b^{th} moment of $\frac{1}{P_R}$ is given as

$$E\left[\left(\frac{1}{P_R}\right)^b\right] = \frac{\left(1 - e^{-\frac{Q}{\mu_{RP} P_m}}\right)^L}{{P_m}^b} + \sum_{r=1}^{L} (-1)^{r+1} \binom{L}{r} \left(\frac{\mu_{RP}}{rQ}\right)^b \Gamma\left(b+1, \frac{rQ}{\mu_{RP} P_m}\right) \tag{6.21}$$

Using the expressions in equations (6.12), (6.13), and (6.20), we can write the asymptotic expression A_1 as follows

$$
\begin{aligned}
A_1 &= E_{P_S}\left[P\left(out|\,D=D_l,P_S\right)P\left(D=D_l|\,P_S\right)\right]\\
&= E_{P_S}\left[\left(\frac{u_1N_0}{\mu_{SD}P_S}\right)\left(\frac{u_2N_0}{\mu_{SR}P_S}\right)^{M-l}\right]\\
&= \left(\frac{u_1u_2^{M-l}N_0^{M-l+1}}{\mu_{SD}\mu_{SR}^{M-l}}\right)\\
&\left[\frac{\left(1-e^{-\frac{Q}{\mu_{SP}P_m}}\right)^L}{{P_m}^b}+\sum_{r=1}^{L}(-1)^{r+1}\binom{L}{r}\left(\frac{\mu_{SP}}{rQ}\right)^b\Gamma\left(b+1,\frac{rQ}{\mu_{SP}P_m}\right)\right]
\end{aligned}
\tag{6.22}
$$

Using the expressions found in equations (6.13), (6.15), (6.20), and (6.21) A_2 can be written as follows

$$
\begin{aligned}
A_2 &= E_{P_S,P_R}\left[\frac{u_2N_0}{P_S\mu_{SD}}\sum_{n=1}^{N}\binom{k}{n-1}\left(\frac{u_2N_0}{P_R\mu_{RD}}\right)^{k-n+1}\right.\\
&\left.\frac{\left(1-\left(1-\frac{u_1}{u_2}\right)^{k-n+2}\right)}{(k-n+2)}\left(\frac{u_2N_0}{P_S\mu_{SR}}\right)^{M-k}\right]\\
&= \sum_{n=1}^{N}\binom{k}{n-1}\frac{(u_2N_0)^{M-n+2}}{\mu_{SD}\mu_{SR}^{M-k}\mu_{RD}^{k-n+1}}\frac{\left(1-\left(1-\frac{u_1}{u_2}\right)^{k-n+2}\right)}{(k-n+2)}\\
&E\left[\left(\frac{1}{P_S}\right)^{M-k+1}\right]E\left[\left(\frac{1}{P_R}\right)^{k-n+1}\right]
\end{aligned}
\tag{6.23}
$$

A_2 can be then be foiund be substituting the expressions for the b^{th} moment of $\frac{1}{P_S}$ and $\frac{1}{P_R}$ into eq.(6.23).

Using equations (6.22) and (6.23) to substitute for A_1 and A_2, the total outage probability of the CRN with DF Incremental relaying and N^{th} best relay is presented in eq.(6.24).

$$
\begin{aligned}
P\left(out\right) = & \sum_{l=0}^{N-1} \binom{M}{l} \left(\frac{u_1 u_2^{M-l} N_0^{M-l+1}}{\mu_{SD} \mu_{SR}^{M-l}} \right) \\
& \left[\frac{\left(1 - e^{-\frac{Q}{\mu_{SP} P_m}}\right)^L}{{P_m}^b} + \sum_{r=1}^{L} \left(-1\right)^{r+1} \binom{L}{r} \left(\frac{\mu_{SP}}{rQ}\right)^b \Gamma\left(b+1, \frac{rQ}{\mu_{SP} P_m}\right) \right] \\
& + \sum_{k=N}^{M} \binom{M}{k} \sum_{n=1}^{N} \binom{k}{n-1} \frac{\left(u_2 N_0\right)^{M-n+2}}{\mu_{SD} \mu_{SR}^{M-k} \mu_{RD}^{k-n+1}} \frac{\left(1 - \left(1 - \frac{u_1}{u_2}\right)^{k-n+2}\right)}{(k-n+2)} \\
& \left[\frac{\left(1 - e^{-\frac{Q}{\mu_{SP} P_m}}\right)^L}{{P_m}^b} + \sum_{r=1}^{L} \left(-1\right)^{r+1} \binom{L}{r} \left(\frac{\mu_{SP}}{rQ}\right)^b \Gamma\left(b+1, \frac{rQ}{\mu_{SP} P_m}\right) \right] \\
& \left[\frac{\left(1 - e^{-\frac{Q}{\mu_{RP} P_m}}\right)^L}{{P_m}^b} + \sum_{r=1}^{L} \left(-1\right)^{r+1} \binom{L}{r} \left(\frac{\mu_{RP}}{rQ}\right)^b \Gamma\left(b+1, \frac{rQ}{\mu_{RP} P_m}\right) \right]
\end{aligned}
\tag{6.24}
$$

CHAPTER 7

Energy-Aware Cognitive Machine-to-Machine Networks with Generalized-Order Relaying

7.1 Introduction

The past decade has witnessed a tremendous increase in the amount of real time information that is exchanged between different users and applications giving rise to the Internet of Things (IoT) Atzori et al. (2010); Stankovic (2014); Al-Fuqaha et al. (2015). The IoT forms large networks of heterogeneous devices and applications that are connected together, these connected networks can be traditional human-to-human communications but can also be human-to-machine communications and machine-to-machine (M2M) communications. In M2M networks, machines generate, exchange, and process data without or with low human interventions. These machines can be radio-Frequency Identification tags, wireless sensor networks, actuators, cellular phones, motor vehicles, surveillance cameras, etc Whitehead (2004); Niyato et al. (2011); Zhang et al. (2012); Aijaz and Aghvami (2015).

The implementation of M2M networks consisting of huge number of devices create several challenges such as spectrum accessing, managing communications with heterogeneous machines, and the meeting energy requirements. Cognitive Machine-to-Machine (CM2M) communications has been proposed to solve some of these challenges Zhang et al. (2012); Aijaz and Aghvami (2015). A CM2M system is composed of two systems utilizing the same frequency range: a primary system which is licensed to use this spectrum and a secondary system that is trying to utilize the same spectrum with limited impact on the performance of the primary system Mitola and Maguire (1999); Haykin (2005); Nekovee (2010). Thus CM2M solves one of the major challenges facing M2M communications which is spectrum scarcity arising from the increasing need for high data rate wireless communications along with the massive increase in the number of connected devices.

Green requirement is another major challenge facing M2M communications. The need for energy efficient systems and devices is crucial to M2M networks since it is composed of mainly low-cost devices that have low-power capabilities. Thus it is very important to include energy efficiency as one of the main aspects when designing M2M networks. CM2M communications have been shown to reduce the energy consumption while maintaining the required quality-of-service He et al. (2009); Hasan et al. (2011).

Cooperative diversity communication techniques have been shown to increase the energy efficiency of wireless communication systems. Cooperative diversity networks create virtual MIMO systems in which the relays extend the coverage of the system with lower transmission power, this in turn generates less interference Laneman and Wornell (2000); Song et al. (2004).

7.2 Energy Efficiency Analysis

The energy efficiency is expressed in Amin et al. (2012) as

$$EE = \frac{P_{tot}}{\overline{R}_E} \tag{7.1}$$

$$\begin{aligned} P_{tot} &= (1-\bar{P}_{P,SD})(1+\alpha)(P_S+P_{ct}+(M+1)P_{cr}) \\ &+ \bar{P}_{P,SD}\bar{P}_{P,SR}((1+\alpha)P_S+P_{ct}+(M+1)P_{cr}) \\ &+ \bar{P}_{P,SD}((1-\bar{P}_{P,SR})(1+\alpha)P_S+(1+\alpha)P_R+(M+1)P_{ct}+(M+2)P_{cr}) \end{aligned} \tag{7.2}$$

where the first term describes the case where the direct transmission on the S-D link is successful and no retransmission is needed. The second term describes the case where the direct transmission fails and retransmission is needed but either none of the relays were able to successfully decode the source message in the first time slot or the number of relays that were able to decode the source message correctly, j, is smaller than the selection order N, i.e. $j < N$. Finally the third term represents the case where a retransmission is needed after the failure of the direct transmission and the N^{th} best relay retransmits the source message in the second time slot. The parameter α represents the ratio between drain efficiency and the peak-to-average ratio and is given as

$$\alpha = \frac{\xi}{\eta - 1} \tag{7.3}$$

where ξ is the drain efficiency and η is the peak-to-average ratio. $\overline{R}_E$ is the average transmission rate of the incremental relaying scenario and is given as

$$\begin{aligned} \overline{R}_E = &\frac{R_T}{2}(1 - P_{P,SR})E\{\delta(\text{S-D error, S-R-D cooperation error free})\} \\ &+ R_T(1 - P_{P,SD}) \end{aligned} \tag{7.4}$$

For Generalized order of selection, M is equal to 1 as only one relay, the N^{th} best relay, is selected to forward the source message to the destination.

The energy efficiency is written as

$$\begin{aligned} EE = &\frac{1}{\bar{R}_E}[(1 - \bar{P}_{P,SD})(1 + \alpha)(P_S + P_{ct} + 2P_{cr}) \\ &+ \bar{P}_{P,SD}\bar{P}_{P,SR}((1 + \alpha)P_S + P_{ct} + 2P_{cr}) \\ &+ \bar{P}_{P,SD}((1 - \bar{P}_{P,SR})(1 + \alpha)P_S + (1 + \alpha)P_R + 2P_{ct} + 3P_{cr})] \end{aligned} \tag{7.5}$$

$P_{P,SD}$ and $P_{P,SR}$ are given as

$$
\begin{aligned}
P_{P,SD} &= \Pr(\gamma_{SD} < {\gamma'}_{th}) \\
&= \Pr(out|\, D = \varnothing, P_S) \\
&= \frac{u_1 N_0}{\mu_{SD} P_S}
\end{aligned}
\tag{7.6}
$$

where $u_1 = 2^{R_{\mathrm{T}}} - 1$.

$$
\begin{aligned}
P_{P,SR} &= \Pr(\gamma_{SR} < \gamma_{th}) \\
&= \Pr(D = \varnothing | P_S) \\
&= (\frac{u_2 N_0}{\mu_{SR} P_S})^M
\end{aligned}
\tag{7.7}
$$

where $u_2 = 2^{2R_{\mathrm{T}}} - 1$.

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