Relay Sensors Selection in Wireless Communication: Bit Error Rate Analysis

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Abstract. Cooperative communication system, which make use of the intermediate relays between the transmitter and the receiver, have been employed as an effective technique to combat the channel fading and to enhance system performance. Cooperative systems have some drawbacks such as high latency and diversity order not guaranteed. To alleviate the negative effects of these factors, relay selection protocol is employed in cooperative communication systems to increase overall cooperative system performance. Relay selection in the cooperative systems enables the source to cooperate with the single relay node rather than multiple relay nodes which guaranteed the diversity order.

1. Introduction
Cooperative networks (CNs) have been grew and gain much attention recently as new model of communication system that make intermediate nodes help the source to retransmitted its data if the source to destination link (SDL) failed due to error propagation or the relay nodes retransmit the source data in addition transmitted source data and the destination combine them together to achieve diversity gain.

In order to achieve the diversity gain through a cooperation, the source broadcast the data to the relay node and to the destination (exploiting the broadcast nature of Wireless medium in CNs), and either the relay nodes process the data that received from the source before retransmitting to the destination, or the relay nodes doesn’t process the data but directly retransmit to the destination. The relay nodes can process the data such that estimation, demodulation and forward, decoding and re-encoding.

Recently, inclusive work on CNs have been inspected as the relay nodes repeat the data to the destination and it receive the data from the relay nodes only has been considered in [1-3], or the destination receive the data from the source and relay nodes has been considered in [4-7]. Generally, if the relay nodes process the data before retransmitting that mean the relay nodes within the range of the source and the destination and such retransmitting, it can cause reduction in the spectral efficiency (degree of the freedom of the channels). Loosely speaking, the cooperation is achieve diversity gain but multiplexing gain may not, if the cooperation system not design properly. Hence it is important to evaluate their performance in the term of diversity-multiplexing trade-off[8].
Since, retransmission the data by the relay nodes to the destination, it is inherently reducing the spectral efficiency. There are several techniques have been explored in the literature to overcome the above problems through distributed space time coding [9,10], relay nodes work on full duplex, it is mean the relay node can receive and transmit at same time [11], dynamic allocation of the time slots [12], best relay selection [13,14]. In the practical, the implementation of distributed space code require to setup multiple antennas at the mobile set and this not practical for small devices, full duplex cooperation required the relay to cancel its self-interference from the received signal, but this not robust in the low cost radio devices, dynamic allocation required overhead and global information, relay selection is simplistic way and can achieve spectral efficiency as well as diversity gain.

The best relay selection (BRS) can generally be categorized into two classes: the reactive BRS [15-17], and proactive BRS [18-20]. The reactive BRS protocol prompts the relay selection process after the source broadcasting the data to the destination and relay nodes. However, the proactive BRS protocol is selecting the relay node before the source broadcasting (transmitting). The disadvantage of the proactive BRS is that relay node retransmits what was transmitted by the source to destination even when the direct transmission is sufficient such a disadvantage reduce the spectral efficiency. Hence designing an efficient and robust BRS can achieve better spectral efficiency.

The contributions of this paper are summarized as follow:
1. We propose a relay selection protocol that select best relay node base on link quality from the source to relay and from the relay to the destination that can gain the cooperation system a better performance.
2. We assume the relay process the data before retransmitting to the destination, where the process type is decoding and re-encoding again that offer extra coding gain to cooperation system and the spectral efficiency.

We reveal the proposed protocol can reduce the bit error rate compared to classical cooperation mode (cooperation without selection protocol) and previous work. The reset of the paper is organized as follow: We provide a channel formulation of decode and re-encode of CNs in the section 2. In the section 3, we present the details and the main idea of a proposed relay selection protocol, in sequel, we evaluate the spectral efficiency, bit error rate, diversity order and outage probabilities of the proposed relay selection protocol in the subsections 3.1, 3.2 and 3.3. Analysis and performance results are addressed in section 4. And finally section 6 draw the conclusion and future work.
802.15.6 standard, then MN transfer what were transmitted by the sensors to the next tier over one of the wireless technology or cables.

Smart Interface (layer#2), in this layer, smart devices are utilized, (i.e., smart phone, laptop or tablet). In this layer, data are inspected and analysed, then the data transferred to layer 3 over one of the selected wireless communication technologies (i.e., Bluetooth, Wi-Fi or cellular Base-station). Layer 2 represent the bridge tier that is connect the WBSN to the infrastructure internet, and some time located within WBSN area. Infrastructure internet layer (layer#3), this level bridge the gap between the layer#2 and layer#4 via exiting communication technology. Care-Services layer (layer#4), in this layer, the received data patient server, the Patient server: in this layer, the data are stored, analyzed and forwarded to the suitable service, such as, emergency, physician, or family.

2. Relay Selection for proposed Architecture

2.1 Inter-Node SNR modelling

In this section, the channel formulation of the decode and forward cooperation is described. In this work, the cooperation take place over two time slot, first time slot sensor broadcast the data over wireless channel using 802.15.6 for second tier and third tier, then at second time slot, the D2D users re-forward the received data to the third tier over 802.11b. In the first time slot, the received signals at the destination \( Y_{t1-t3} \) and relay \( Y_{t2-t3} \) are given as

\[
Y_{t1-t3} = \sqrt{\bar{P}_b} h_{t1-t3} x + \eta_{t1-t3},
\]

\[
Y_{t1-t2} = \sqrt{\bar{P}_b} h_{t2-t3} x + \eta_{t2-t3}.
\]

The \( h_{t1-t3}, h_{t1-t2} \) are the fading coefficients for corresponding tier#1 to tier#3 and tier#1 to tier#2 links, respectively; \( x \) is the modulated signal transmitted from the source, and \( \eta_{t1-t3}, \eta_{t2-t3} \) are the complex white Gaussian noise with zero mean and unit variance for corresponding tier#1 to tier#3 and tier#1 to tier#2 links, respectively. In the second time slot, The signal received at the destination \( Y_{rd} \) from the relay is given as

\[
Y_{t2-t3} = \sqrt{\bar{P}_m} h_{t2-t3} \hat{x} + \eta_{t2-t3}.
\]

The \( h_{t2-t3} \) is the fading coefficient for corresponding tier#2 to tier#3 link, \( \hat{x} \) is the modulated signal transmitted from the relay to the destination, and \( \eta_{t2-t3} \) is the complex white Gaussian noise with zero mean and the unit variance for corresponding tier#2 to tier#3 link. In what follow, the instantaneous received signal-to-noise ratio of the three links, tier#1 to tier#3 and tier#1 to tier#2 and tier#1 to tier#2 links, are given below as:

\[
\gamma_{t1-t3} = \frac{P_b}{N_0} |h_{t1-t3}|^2.
\]

\[
\gamma_{t1-t2} = \frac{P_m}{N_0} |h_{t2-t3}|^2.
\]

\[
\gamma_{DF} = \frac{P_b}{N_0} |h_{t2-t3}|^2 + \frac{P_m}{N_0} |h_{t2-t3}|^2.
\]

2.2 Relay Selection

In this section, the proposed best D2D Users Selection (BD2DS) algorithm is described. The proposed BD2DS algorithm operation is modified version of the traditional automatic repeat request (ARQ) algorithm, if the tier#3 device transmits a negative ACK to the sensors (tier#1 device) indicating the failure of the reception, the tier#2 device retransmit the lost signal tier#3 device, then tier#3 device sum-u the signals via Maximal Ratio Combing (MRC). Accordingly, The BD2DS algorithm in this paper can be summarized as follow; 1) the tier#3 device admit a direct transmission signals‘ (tier#1 to tier#3), if the link quality of tier#1 to tier#3 greater than the links quality of tier#1 to tier#2 and tier#2 to tier#3, 2) the best D2D users‘ do retransmission if the link quality of tier#1 to tier#3 less than the links quality of the tier#1 to tier#2 and tier#2 to tier#3. Thus, the BD2DS selection methodology can be mathematically modeled as
In this section, it is shown the BD2DS algorithm has diversity order is 2, in which single relay has been chosen within relay region. General definition of the error probability between two nodes \((i; j)\) given algorithm can be upper bounded by removing the negative term and setting

\[
\mu = \beta_{\ell_1-\ell_3} > \beta_{\text{max}}. \tag{7}
\]

Let \(\beta_{\ell_1-\ell_3}\) be a common channel coefficient representing the channel between any given two nodes. \(\beta_{\ell_1-\ell_3}\) is modeled as zero-mean complex Gaussian random variables with variance \(\sigma_{\ell_1-\ell_3}\). The \(\beta_{\min-\max} = \min\{max\{\beta_1, \beta_2, \ldots, \beta_k\}\}, \beta_k = \max\left(\frac{\sigma_{\ell_1-\ell_3}^2}{d_{\ell_1-\ell_3}^2}, \frac{\sigma_{\ell_2-\ell_3}^2}{d_{\ell_2-\ell_3}^2}\right)\), in which \(k = 1, 2, \ldots, L\) is the number of the D2D users in the tier#2. Based on the event given in (7), the proposed BD2DS algorithm can be described as follows; after the sensors broadcasting the data to the destination and D2D users. In the second time slot, the tier#3 device checks the criteria given in (7), and if the criteria \(\beta_{\ell_1-\ell_3} > \beta_{\min-\max}\) is satisfied the tier#3 device resolves the transmitted data and transmits positive ACK, otherwise the tier#3 device transmits negative ACK. In the latter case the best D2D users node re-transmits its decoded re-encoded data. The tier#3 device is assumed has knowledge of the links quality of the tier#1 to tier#2 and tier#2 to tier#3 of all D2D users.

### 2.3 Bit Error Rate Formation of the Proposed Method

In this section, it is shown the BD2DS algorithm has diversity order is 2, in which single relay has been chosen within relay region. General definition of the error probability between two nodes \((i; j)\) given as [1]

\[
P_e = Q\left(\sqrt{A|h_{i,j}|^2}\right) \leq 1 \int_0^{\frac{M-1}{M}} e^{-A A_0|h_{i,j}|^2} \, d\theta \tag{8}
\]

In which the \(A = k_{psk} P_b\), \(kpsk = (\sin(\pi/M)) / No, M\) is the modulation order, and \(A_0 = (1 / \sin^2(\theta)) \). The expression of error probability of a decode and forward algorithm consists of two parts: 1) the source broadcasts the data to the destination and relays, but relay does not forward to destination the data that received from the source since the destination send positive ACK to relay, 2) the destination receives the data from source and relays since it send negative ACK to relay. Therefore, considering these cases, the error probability of DF algorithm is given as [23]

\[
P_e^{DF} = Q\left(\sqrt{A|h_{\text{rel}}|^2}\right) + \sum_{k=1}^L Q\left(\sqrt{A|h_{\text{rel}}|^2 + A|h_{\text{rel}}|^2}\right) \times \prod_{k=1}^L 1 - Q\left(\sqrt{A|h_{\text{rel}}|^2}\right) \tag{9}
\]

In which \(1 - Q\left(\sqrt{A|h_{\text{rel}}|^2}\right)\) is error-free of tier#1 to tier#2 link. The probability of error of DF algorithm can be upper bounded by removing the negative term and setting \(L = 1\) we rewrite (9) as [26]

\[
P_e^{DF} = \frac{1}{\pi^2} \int_0^{\frac{M-1}{M}} \frac{M^{\frac{M-1}{M}}}{\pi^2} \exp\left(-A A_0|h_{\text{rel}}|^2\right) \, d\theta \tag{10}
\]

The error probability of BD2DS algorithm can be express as [29]

\[
P_e^{DF} = P_e^{bp}\overline{P(\mu)} + P_e^{TP}\overline{P(\mu)} \tag{11}
\]

The first term of (24) is comprised from two multiplied terms, the probability of error of the broadcasting phase ‘\(P_e^{bp}\)’ and the probability of the correct reception from the broadcasting phase ‘\(P(\phi)\)’. The first term can be express as

\[
P_e^{bp} P(\mu) = \int_0^\infty P(e|\mu) \Pr\left(\mu \left| \frac{K_{\text{ed}}}{L_{\text{ed}}} \right\right) p_{\text{ed}}(L_{\text{ed}}) \, dL_{\text{ed}} \, dL_{\text{sr}} \tag{12}
\]
The \( Pr(e|\psi) \) is given in (23) as broadcasting phase term, \( Pr(\psi|l_{sd}/l_{rd}) = \left(1 - \exp((-\gamma_1 + \gamma_2)l_{sd}/\lambda)\right) \) and \( p_{sd}(l_{sd}) = (1/\sigma_{sd})\exp(-l_{sd}/\sigma_{sd}) \), we rewrite (25) as:

\[
Pr(e|\psi)_{\text{term(1)}}Pr(\psi) = \frac{1}{\sigma_{sd}} \int_0^\infty \exp(-Al_{sd}) \left(1 - \exp\left(-\frac{l_{sd}}{\lambda}(\gamma_1 + \gamma_2)\right)\right) d\theta d\psi dl_{sd} dl_{sr} \quad (13)
\]

Then (26) can be upper bounded by setting \( \theta = 1 \) and \( \int_0^{(M-1)\lambda} \int_0^{(M-1)\lambda} d\theta d\psi = \left(\frac{M-1}{\lambda}\right)^2 \) [27], [28], then we rewrite (13) as:

\[
p_e^{BP} Pr(\mu) \leq \frac{m}{\kappa_{psk}A_p\sigma_{tr}^2} \int_0^{\infty} \exp\left(-A l_{sd} - \frac{l_{sd}}{\sigma_{sd}}\right) \exp\left(-A l_{sr}\right) \left(1 - \exp\left(-\frac{l_{sd}}{\lambda}(\gamma_1 + \gamma_2)\right)\right) dl_{sd} dl_{sr} \quad (14)
\]

Solving the integration of (14) with respect to \( l_{sd}, Isr \) and substitute \( \gamma_1 \) and \( \gamma_1; \) further, SDL is assumed to be fixed during the cooperation, as followwe set \( \sigma_{sd}^2 = 1 \). We rewrite (14) as:

\[
p_e^{BP} Pr(\mu) \leq \frac{m}{\kappa_{psk}A_p\sigma_{tr}^2} \left(A \sigma_{sr}^2\right)^{-1} - \bar{m} \left(1 + A + \frac{1}{\lambda} \left(\sigma_{tr}^2 + \sigma_{rd}^2\right)\right)^{-1} \quad (15)
\]

In which \( \bar{m} \) is \( \left(\frac{M-1}{\lambda}\right)^2 \).

The second term of (9) is comprised from two multiplied terms, the probability of error of the MRC \( 'P_e^{BP}' \) and the probability of the correct reception from the both relay and direct transmission \( 'P(\tilde{\mu})' \). can be express as [30]

\[
P_e^{BP} \tilde{P}(\tilde{\mu}) = \int_0^\infty p(e|\tilde{\mu}) Pr(\tilde{\mu}|\tilde{I}) p_\tilde{I}(\tilde{I}) d\tilde{I} \quad (16)
\]

In which \( \tilde{I} = [l_{sd}, l_{sr}, l_{rd}], Pr(\tilde{\mu}|\tilde{I}) \) is the probability of the BD2DS algorithm protocol and it is given as [31]

\[
Pr(\tilde{\mu}|l_{sd}, l_{sr}, l_{rd}) = Pr(l_{sd} < \lambda l_{max}^{rd}) = 1 - \exp\left(-\left(\frac{A A_0 + \frac{1}{\lambda} \lambda l_{max}^{rd}\right)\lambda l_{max}\right) \quad (17)
\]

\( p(e|\tilde{\mu}) \) is second term of the (23), and \( p_\tilde{I}(\tilde{I}) = p(l_{sd}) p(l_{sr}) p(l_{rd}) \); we rewrite (17) as:

\[
p_e^{BP} \tilde{P}(\tilde{\mu}) \leq \int_0^\infty \exp(-A A_0(l_{sd} + l_{rd})) \left(1 - \exp\left(-\left(\frac{A A_0 + \frac{1}{\lambda} \lambda l_{max}\right)l_{max}\right)\right) dl_{sd} dl_{sr} dl_{rd} \quad (18)
\]

Evaluate the integration with respect to \( l_{sd} \) and we take into account the upper bound assumption that is made on (14), we rewrite (18) as:

\[
p_e^{BP} \tilde{P}(\tilde{\mu}) \leq \bar{m} \int_0^A \left(1 - \exp\left(-A + 1\right)\lambda l_{max}\right) p_\tilde{I}(\tilde{I}) dl_{sd} dl_{sr} dl_{rd} \quad (19)
\]

in which \( \bar{m} = M/(M-1) \); taking into account worst case state by substituting \( Isr = k \) Imax and \( l_{rd} = k \) Imax , where \( r, i.e., Pr(e|k=0.1 > Pr(e|k=0.2 > ... > Pr(e|k=0.9 > Pr(e|k=1) \), then we rewrite (19) as:

\[
Pr(e|\psi_{DEC})_{\text{term(2)}}Pr(\psi_{DEC}) \leq \bar{m}(A + 1)^{-1} \int_0^{\lambda l_{max}} \exp(-A k l_{max}) \left(1 - \exp\left(-A + 1\right)\lambda l_{max}\right) dl_{max} \quad (20)
\]

Given a moment generating function of \( I_{\text{max}} \), \( M_{\text{max}}(\cdot) \) [27], we can rewrite (20) as:

\[
Pr(e|\psi_{DEC})_{\text{term(2)}} \leq \bar{m}(A + 1)^{-1} \left(M_{\text{max}}(A k) - M_{\text{max}}(A + \lambda A + \lambda)\right) \quad (21)
\]

The Imax is constitute two random variables are Isr and Ird, and the moment generating function of two independent random variables is given as: \( Mx, My(s,t) = Mx(s)My(t) \), then we rewrite (21) as:
\[
Pr(e | \psi_{DF})Pr(\psi_{DF})_{\text{Term}(2)} \leq \bar{m}(k_{psk} A \rho P_b + 1)^{-1} \omega_{\sigma} \left[ \left( \frac{d_{\rho} \sigma_{\rho}}{\sigma_{\rho}^2} + F(P_b) \right)^{-1} \left( \frac{d_{\rho} \sigma_{\rho}}{\sigma_{\rho}^2} + F(P_b) \right)^{-1} \right]
\]

\[
\left( \frac{d_{\rho} \sigma_{\rho}}{\sigma_{\rho}^2} + F(P_b, P_m) \right)^{-1} \left( \frac{d_{\rho} \sigma_{\rho}}{\sigma_{\rho}^2} + F(P_b, P_m) \right)^{-1}
\]

in which \( \omega_{\sigma} = \left( \frac{d_{\rho} \sigma_{\rho}^2 + d_{\rho} \sigma_{\rho}^2}{\sigma_{\rho}^2} \times \sigma_{\rho}^2 \right) \), \( F(P_m) = k_{psk} P_m \sigma_{\rho} \), and \( F(P_b, P_m) = (k_{psk} P_m k + k_{psk} P_m k + k) \). Finally, total error probability of BD2DS algorithm is obtained by adding the (18) and (22), it is given as

\[
Pr(e) \leq \bar{m}(A + 1)^{-1} \left( \bar{m} A \left( \frac{d_{\rho} \sigma_{\rho}}{\sigma_{\rho}^2} \right)^{-1} - \bar{m} \left( 1 + A + \frac{1}{\lambda} \left( \frac{d_{\rho} \sigma_{\rho}}{\sigma_{\rho}^2} + \frac{d_{\rho} \sigma_{\rho}}{\sigma_{\rho}^2} \right)^{-1} \right) \right)
\]

\[
\omega_{\sigma} \left[ \left( \frac{d_{\rho} \sigma_{\rho}}{\sigma_{\rho}^2} + F(P_b) \right)^{-1} \left( \frac{d_{\rho} \sigma_{\rho}}{\sigma_{\rho}^2} + F(P_b) \right)^{-1} \right] - \left( \frac{d_{\rho} \sigma_{\rho}}{\sigma_{\rho}^2} + F(P_b, P_m) \right)^{-1} \left( \frac{d_{\rho} \sigma_{\rho}}{\sigma_{\rho}^2} + F(P_b, P_m) \right)^{-1}
\]

(23)

3. Simulation and Results

It is clear that, as the selection criteria consider both distances and links quality, the cooperation probability is higher compare to case that considering one of the channel characteristics, i.e., either distance or channel gain. Figure 2 shows the bit error rate compares to signal-to-noise ratio (SNR), the important results apparent in figure can be summarized as follow: The bit error rate reduces once the classical cooperation employed compare to direct transmission. The bit error rate reduce more compare to classical cooperation mode in the previous case, further enhancement as selection consider the best relay node in mid distance among the source and the destination. Selecting a node far away from the source or the destination (not in the middle location between source and destination), the performance reduce from the case as we select the node at the mid distance among the source and the destination.
Figure 2. Bit Error Rate for Direct Transmission

4. Conclusion
In this paper, we have proposed a relay selection protocol for cooperative networks. The advantage of the cooperation and relay selection can be exploited. The relay selection criteria based on maximum link from the source to relay and from the relay to the destination, we demonstrated that the proposed relay selection can substantially improve the spectral efficiency, bit error rate, diversity order and outage probability comparing with non-selective cooperative networks.

References
[1] Liu P, Tao Z, Narayanan S, Korakis T, and Panwar S S 2007 IEEE J. Selected Areas in Comm. 25 340
[2] Yindi J and Hamid J 2009 IEEE T Wirel. Commun. 8 1414
[3] Murad K, Yufeng W, In-ho R, Ravi S 2011 IEEE T. Vehicular Technology 60 3361
[4] Mao M, Cao N, Chen Y. Zhou Y 2015 Wireless Communications Letters, IEEE 4 701
[5] Roua Y and Alexandre G A 2011 IEEE T. Wirel. Commun. 10 253
[6] Wei Z, Yabo L, Xiang G X, Ching P C and Khaled B L 2008 IEEE T. Wirel. Commun. 7 995
[7] Li Y 2006 IEEE J Sel. Area Comm. 24 112040
[8] Lizhong Z and David N C 2003 IEEE T Inform Theory 49 1073
[9] Laneman J N and Wornell G W 2003 IEEE T Inform Theory 49 2415
[10] Jing Y and Hassibi B 2006 IEEE T. Wirel. Commun 5 3524
[11] Yi L, Xiang G X, Hailin Z 2012 IEEE T. Wirel. Commun. 11 2680
[12] Ochiai H, Mitran P and Tarokh V 2006 IEEE T Inform Theory 52 4299
[13] Beres E. and Adve R 2008 IEEE T. Wirel. Commun 7 118
[14] Bletsas, Khisti A and Win M 2008 IEEE T. Wirel. Commun. 7 1823
[15] Xiaoyan W and Jie L 2014 IEEE Trans. Parallel Distrib. Syst. 25 167
[16] Wang J, Zhai H, Fang Y, Shea J and Wu D 2006 IEEE Trans. Mobile Computing 5 1764
[17] Li S, Yeung R., and Cai N 2006 IEEE T Inform Theory 49 371
[18] Wang J, Zhai H, Fang Y, Shea J and Wu D 2006 IEEE Trans. Mobile Computing 5 1764
[19] Ibrahim S, Han Z and Liu K J R EEE Trans. Wirel.Comm. 7 3930
[20] Zhu H and Cao G 2011 *IEEE Trans. Mobile Computing* **5** 1201
[21] Ibrahim S, Sadek A K, Su W and Liu K J R 2008 *IEEE Trans. on Wireless Comm.* **7** 2814
[22] Elfitiuri M, Hamouda W and Ghayeb A 2009 *IEEE Trans. Veh. Techn.* **58** 655
[23] Proakis J G 2002 *Communication System Engineering* (New York: Prentice-Hall) p 600
[24] Aggelos B, Ashish K, David P R and Andrew L 2012 *IEEE J Sel. Area Comm.* **24** 659
[25] Simon M K and Alouini M S 2000 *Digital Communication over Fading Channels: A Unified Approach to Performance Analysis* (New York: Wiley) p 54
[26] Andrea G 2000 *Wireless Communication* (London: Cambridge University Press) p 171
[27] Mohammad J, Ahmadreza H, Todd E H and Aria Nosratinia 2004 *IEEE T. Signal Process.* **52** 362
[28] Kyoung L N, Erchin S and Bruce W S 2007 *IEEE T. Wirel. Commun.* **6** 1654
[29] Nicholas L J, David N C T, Gregory W W 2004 *IEEE T Inform. Theory* **50** 3062
[30] Fakhira, W. N. & Fadzly, M. K. 2019 *AIP Conference Proceedings* **2129** p 020150.
[31] Frenger P, Orten P and Ottosson T 1999 *IEEE Commun. Lett.* **3** 317