Channel Uncertainty Effects on Multihop AF and DF Wireless Mobile Networks

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***Abstract*—The main purpose of this paper is studying both the regenerative decode-and-forward (DF) and non-regenerative amplify-and-forward (AF) schemes for mobile wireless relay network under channel uncertainty. A wireless system consisting of one-source-one-destination mobile pair and N multihop mobile relay nodes is under investigation. The scenario being studied is appropriate for low power or widely spread network of mobile nodes, such as vehiculars, where transmitted signal can reach its first tier nodes only and degrades before reaching its second tier neighbors. Therefore, unlike previous work in the literature, this paper studies a system where no direct link exists between any node and its second tier neighbors. New proposed detection schemes, utilizing the maximum ratio combiner (MRC) principle, are proposed and designed for such a network with uncertain mobile channels. It is applied at both relays and the destination to optimally detect the received signals. Using the new proposed detection scheme, Monte-Carlo simulations are employed, and bit error rate (BER) simulation results are presented to evaluate the system performance under study. Performance comparisons for only source-relay links and for only relay-destination links under channel uncertainties were incorporated as well.**

***Index Terms*—Wireless relay network, decode-and-forward, amplify-and-forward, channel uncertainty, maximum ratio combiner, mobile-to-mobile, cascaded Rayleigh.**

I. Introduction

Different functionalities for relays were proposed in wireless networks. Depending on relay roles in [1]-[13], relays can be classified into; 1) regenerative decode-and-forward (DF) and its variants; 2) nonregenerative amplify-and-forward (AF) and its variants; and 3) compress-and-forward. Using the nonregenerative AF relay method that is applied in this current paper, each relay transmits an amplified copy of its received signal from its preceding node. This tactic doesn't involve any decoding or signal processing; relays can only buffer its received signal in first stage and transmit it in the second stage. Stages of transmission are presented in more detail later in the paper. On the other hand, the regenerative DF relay strategy, which is applied in this current paper, involves complete decoding of received signal at relays in the first stage and reencoding before retransmission in the second stage.

Channel uncertainties for both cooperative and non-cooperative AF and DF wireless relay networks were studied in [8], [14]-[16]. Different system setups were examined such as single-input-single-output, single-input-multiple output, and multiple-input-multiple-output. The influence of channel uncertainty was studied using the minimum mean square error criterion between the original transmitted message from the source and the message component of the received signal at the destination.

In [11], the authors analyzed a regenerative multi-hop DF wireless relay network without the source-destination direct link. However, there is no literature on the regenerative DF and nonregenerative AF for wireless relay networks without the source-destination direct link under channel uncertainty.

In [17], moment generation functions, bit error probability (BEP) and outage probabilities were derived for both single-branch and multi-branch multihop DF cooperative systems in Rayleigh fading channels. Diversity in multihop AF and DF noncooperative systems was studied in [18]. Authors suggested each relay uses all signals from preceding nodes in the chain to achieve diversity before transmission. They proposed upper bounds for BEP and outage probability. In [19], dual-hop AF nonregenerative relays systems with fixed gains were investigated in terms of outage probability and average BEP. Work was done when relays have random fixed gains in Rayleigh fading environments. Authors derived closed form expressions for the average probability error rate and the outage probability. The authors in [20] proposed closed form expressions for outage probability and BEP for single-branch multihop and multihop multibranch for AF non-cooperative wireless network with fixed gains at relays. It was shown that if the average signal-to-noise ratio (SNR) in individual links is above specific thresholds, multihop system can outperform a single hop system. And, diversity gain can be achieved in multi-branch and multi-branch multihop systems.

DF for multihop multibranch noncooperative networks was studied in [11]. Authors presented a new coherent MRC based detector at destination and proposed a lower bound for BEP. It was claimed that by using the new MRC detector at destination, similar performance can be obtained to a system employing Maximum likelihood detector. Authors considered that if a message sent from the source and arrives at the destination through different source-relay-destination paths, it can be called cooperation. In contrast to literature, they misused the cooperative definition in their paper.

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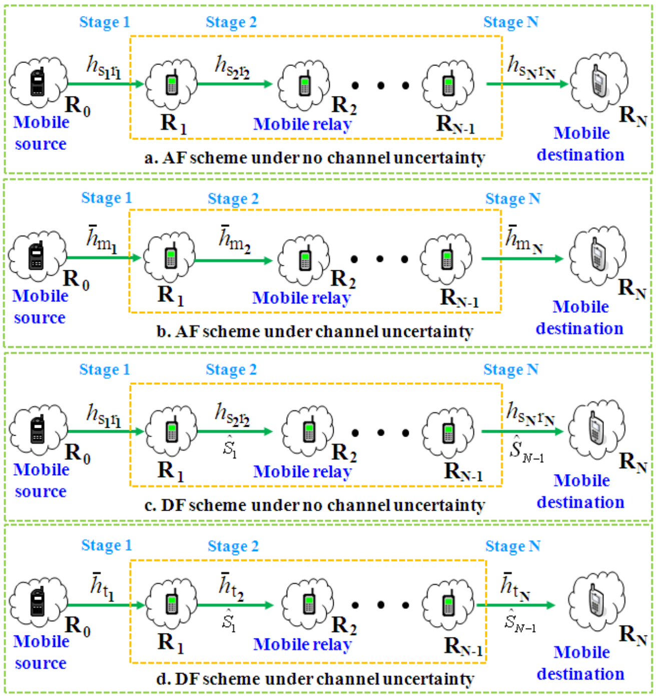

Fig. 1. A multihop AF and DF wireless mobile network with one-source-one-destination mobile pair and N-multihop mobile relay nodes under both no channel uncertainty and channel uncertainty.

Performance of noncooperative multihop DF systems was investigated in [21]. Authors studied S NR and number of hops impact on outage probability of a system. They claimed that lowering SNR while increasing the number of hops results in a lower outage probability. Authors proposed closed form expressions for probability of bit error for minimum phase shift keying modulation. Again, authors misused the cooperation definition in their paper. In [22], the authors investigated multihop DF relaying systems with Rayleigh fading channels. BEP performance was studied for M-ary quadrate amplitude modulation. They derived a compact form of the PDF for the end-to-end SNR and probability of bit error. Authors in [21], [22] observed that the higher the number of hops the better the resulted BEP performance. It is worth to state that this true only when the destination receives copies from all relays hops. The observed BEP improvement was due to diversity gains, and clearly shown in their results. This diversity gain is fixed and depends on number of received signal copies at destination.

Multi-hop relay networks can be classified as channel assisted amplify-and-forward (CA-AF) relays, and fixed gain amplify-and-forward (FG-AF) relays [19], [23]. Similar work to [22] was done in [23], where authors derived BEP for multihop system with Nakagami-m fading channels. Work was done for blind-AF and semi-blind-AF for multi-hop FG-AF relay networks. In the blind-AF, relay uses a fixed gain whereas the semi-blind-AF uses a gain based on the average SNR of the previous hop.

Multi-hop orthogonal frequency division multiplexing relaying systems employing either DF or AF protocols was studied in [24], [25]. An adaptive power allocation algorithm under joint transmits power constraint at source and relays were proposed to increase system capacity and minimize outage probability. Their new algorithms have low complexity and achieve similar performance to other existing ones.

Mainly, there are two available approaches to simulate a statistical mobile-to-mobile small scale fading channel. In [26], authors proposed a channel model and called it “double-ring”. It is based on two rings of uniformly distributed scatters, one around the source and the second around the destination. In mobile ad-hoc wireless network or in a vehicular-to-vehicular communication scenario, the source, relay, and destination are constantly moving. Therefore, it is more realistic to represent the mobile channel by two independent set of scatters; one set around the source, and the other around the destination. In particular, the cascaded Rayleigh channel model represents the second approach for mobile-to-mobile scenario. Although the cascaded Rayleigh concept for this approach was initially suggested in [27], the cascaded Rayleigh model that meet the desired statistical properties was formally proposed in [28]. Small scale measurements were reported in [29], [30] and recommended a cascaded Rayleigh channel to model mobile-to-mobile communication scenarios.

In this current paper, all nodes transmit every other time slot while listen in between. In the first time slot, the source transmits its message while its first hop neighbor relay listens to the medium. During this time slot, the first hob relay receives the signal and stores it for the next time slot in case of AF. Or, decode the received signal using the new proposed MRC detector, reencode then store in the DF case. During the second time slot, the relay transmits its stored message, while the source and the second hop relay listen. In the third time slot, both the source and the second hop relay transmit while the first hop relay listens. While, the source transmits a new message, the second hob relay transmits its stored message from the previous time slot.

One technique to guarantee no interference or collision at relays and destination during reception, is by assuming that all nodes are far from each other or relays operate at low power. In this case, signal transmitted from the source degrades before it reaches relays in the second and higher tiers. Similarly, the transmitted signal from first relay fades before it reaches relays in the second or higher tiers. A vehicular-vehicular communication in a highway scenario is a good example.

The scenario repeats itself until the last relay hop in the network. Since, each relay listen in one time slot and transmits in the next one; this assure fixed and minimum total delay in delivering the original transmitted message from the source to the destination. The total delay will eventually depend only on the number of hops in a network. Finally, using new proposed MRC based detectors at the destination, messages are optimally detected.

In summary, similarly to work that was done for AF systems in [8], [15], [16]; this current paper studies the regenerative DF and nonregenerative AF wireless relay scheme under channel uncertainty in a multihop mobile scenario. As was done in [15], [16], the regenerative DF and nonregenerative AF multi-hop mobile relay network without the source-destination direct link under channel uncertainty is a main focus in this current paper. Motivated by the existing maximum ratio combiner MRC detection scheme in [11]-[13], new MRC based detection schemes are proposed and applied, at relays and the destination. To the authors' knowledge, The work in this paper is novel and no literature was found to compare with this particular system setup.

Notation: The complex conjugate of any scalar a is denoted by a^*. Notation $|a|$ denotes the absolute value of any scalar a. A $\arg\min_a |\cdot|$ denotes the value of a at which is $|\cdot|$ is minimized. The cardinality of the M-ary constellation is denoted by $|\boldsymbol{A}_a| = M$. The product of a sequence $x_1 \cdot x_2 \cdot \ \cdots \ x_{M}$ is denoted by $\prod_{m=1}^{M} x_m$.

II. System Model and Detection Strategies

A. AF Scheme under No Channel Uncertainty

Figure 1(a) shows an AF wireless mobile network under no channel uncertainty with a one-source-one-destination mobile node pair and N-multihop mobile relay nodes.

Let perfect channel complex coefficients h_{s_i} and h_{r_i} denote Rayleigh fading channels with zero-mean and unit variance, respectively. However, the perfect channel complex coefficient product $h_{s_i}h_{r_i}$ is cascaded Rayleigh fading channels. In order words, products $h_{s_1}h_{r_1}$ and $h_{s_N}h_{r_N}$ are, respectively, mobile-to-mobile channels from source node to the first relay node and from $(N-1)$-th relay node to destination node, while $h_{s_i}h_{r_i}, i = 2, \cdots, N-1$, denotes mobile-to-mobile channel from the $(i-1)$-th relay node to i-th relay node.

As shown in Fig. 1(a), there are N stages for data transmission. In stage 1, a source node transmits a signal s to the first relay node during the first time slot, where R_0 in Fig. 1(a) is a source node. Then, in stage 2, the first relay node forward its received signal from the source node to the second relay node during the second time slot. This procedure will be consecutively repeated until the last relay node forwards its received signal from the $(N-1)$-th relay node to the destination node in stage N, where the relay node in Fig. 1(a) represents from R_1 to R_{N-1}, and the destination node in Fig. 1(a) is R_N, respectively.

Therefore, the received complex signal $y_{r_{1\text{–}AF}} \in \mathbf{C}^{1\times1}$ at the first relay node under no channel uncertainty is written as

$$y_{r_{1\text{–}AF}} = h_{s_1}h_{r_1}s + v_{r_1} \tag{1}$$

where $v_{r_1} \in \mathbf{C}^{1\times1}$ is a zero-mean complex additive white Gaussian noise (CAWGN) random variable with variance $\sigma^2_{v_{r_1}}$. The subscript $_{AF}$ means the case of the AF wireless mobile network. Then, the received complex signal $y_{r_{2\text{–}AF}} \in \mathbf{C}^{1\times1}$ at the second relay node under no channel uncertainty is written as

$$y_{r_{2\text{–}AF}} = \alpha_1 h_{s_2}h_{r_2}y_{r_{1\text{–}AF}} + v_{r_2}. \tag{2}$$

where $v_{r_2} \in \mathbf{C}^{1\times1}$ is a zero-mean CAWGN random variable with variance $\sigma^2_{v_{r_2}}$ and α_1 is the amplification coefficient at the first relay node. Then, the received complex signal $y_{r_{i\text{–}DF}} \in \mathbf{C}^{1\times1}$ at the i-th relay node under no channel uncertainty is written as

$$y_{r_{i\text{–}AF}} = \alpha_{i-1} h_{s_i}h_{r_i}y_{r_{(i-1)\text{–}AF}} + v_{r_i} \tag{3}$$

where $v_{r_i} \in \mathbf{C}^{1\times1}, i = 2, \cdots, N-1$, is also a zero-mean CAWGN random variable with variance $\sigma^2_{v_{r_i}}$ and α_{i-1} is the amplification coefficient at the $(i-1)$-th relay node. Finally, the received complex signal $y_{d\text{–}AF} \in \mathbf{C}^{1\times1}$ at the destination node under no channel uncertainty during the N time slots can be written as

$$y_{d\text{–}AF} = \alpha_{N-1} h_{s_N}h_{r_N}y_{r_{(N-1)\text{–}AF}} + v_{r_N} \tag{4}$$

where v_{r_N} is also a zero-mean CAWGN random variable with variance $\sigma^2_{v_{r_N}}$ and α_{N-1} is the amplification coefficient at the $(N-1)$-th relay node. Consequently, the originally transmitted message s from the source node is detected at the destination node under no channel uncertainty using the MRC detection as

$$\begin{aligned}\hat{s}_{D\text{–}AF} = \arg\min_{s\in\boldsymbol{A}_s} \Big| \alpha_T \Big(\prod_{i=1}^{N} h^*_{s_i}h^*_{r_i}\Big) y_{d\text{–}AF} \\ - \alpha^2_T \Big(\prod_{i=1}^{N} |h_{s_i}|^2|h_{r_i}|^2\Big)s\Big|^2\end{aligned} \tag{5}$$

where

$$\alpha_T = \sqrt{\frac{\sigma^2_s}{\alpha^\dagger + \sigma^2_{v_{r_T}}}}. \tag{6}$$

where $T = N-1$. Here, $\alpha^\dagger$ is defined as

$$\begin{aligned}\alpha^\dagger = \sigma^2_s \prod_{i=T-1}^{1} \alpha^2_i \prod_{k=T}^{1} |h_{s_k}|^2|h_{r_k}|^2 \\ + \sum_{t=2}^{T}\Big(\Big[\prod_{i=T-1}^{t-1}\alpha^2_i \prod_{k=T}^{t}|h_{s_k}|^2|h_{r_k}|^2\Big]\sigma^2_{v_{r_{t-1}}}\Big)\end{aligned} \tag{7}$$

when $T \geq 2$, and $\alpha = \sqrt{\frac{\sigma^2_s}{\sigma^2_s|h_{s_1}|^2|h_{r_1}|^2+\sigma^2_{v_{r_1}}}}$ when $T = 1$, i.e., $\alpha = \alpha_1$.

B. AF Scheme under Channel Uncertainty

Figure 1(b) illustrates an AF wireless mobile network under channel uncertainty with a one-source-one-destination mobile node pair and N-multihop mobile relay nodes. In reality, due to channel estimation errors, as shown in Fig. 1(b), the imperfect channel complex coefficient $\bar{h}_{m_i}$ should be applied as

$$\bar{h}_{m_i} = h_{m_i} - \phi_{m_i} \tag{8}$$

where $h_{m_i} \triangleq h_{s_i} h_{y_i}$ and ϕ_{m_i} is the channel estimation error consisting of complex independent identically distributed (i.i.d.) cascaded Rayleigh fading channel with zero-mean and variance $\sigma^2_{\phi_{m_i}}$. The estimated channel errors are employed in all links, respectively. Therefore, using (8), the received complex signal $\hat{y}_{r_{1\text{–}AF}}$ at the first relay node under channel uncertainty, $\hat{y}_{r_{i\text{–}AF}}$ at the i-th relay node under channel uncertainty, and $\hat{y}_{d\text{–}AF}$ at the destination node under channel uncertainty are, respectively, written as

$$\hat{y}_{r_{1\text{–}AF}} = \bar{h}_{m_1} s + \phi_{m_1} s + v_{m_1} \tag{9}$$

$$\hat{y}_{r_{i\text{–}AF}} = \beta_{i-1} \bar{h}_{m_i} y_{r_{(i-1)\text{–}AF}} + \beta_{i-1} \phi_{m_i} y_{r_{(i-1)\text{–}AF}} + v_{m_i} \tag{10}$$

and

$$\hat{y}_{d\text{–}AF} = \beta_{N-1} \bar{h}_{m_N} y_{r_{(N-1)\text{–}AF}} + \beta_{N-1} \phi_{m_N} y_{r_{(N-1)\text{–}AF}} + v_{m_N} \tag{11}$$

where $v_{m_1}, \cdots, v_{m_N}$ are zero-mean CAWGN random variables with variance $\sigma^2_{v_{m_1}}, \cdots, \sigma^2_{v_{m_N}}$, respectively. In addition, β_{i-1} and β_{N-1} is the amplification coefficient under channel uncertainty at the $(i-1)$-th and $(N-1)$-th relay node, respectively. The superscript hat ($\hat{}$) in $y_{r_{1\text{–}AF}}$, $y_{r_{i\text{–}AF}}$, and $y_{d\text{–}AF}$ is the case of the AF wireless mobile network under channel uncertainty.

Consequently, the originally transmitted message s from the source node is detected at the destination node using the MRC detection as

$$\hat{s}_{D\text{–}AF} = \arg\min_{s \in \boldsymbol{A}_s} \Big| \beta_T \Big(\prod_{i=1}^{N} \bar{h}^*_{m_i} \Big) y_{d\text{–}AF} - \beta^2_T \Big(\prod_{i=1}^{N} |\bar{h}_{m_i}|^2 \Big) s - \beta^2_T \Big(\prod_{i=1}^{N} |\phi_{m_i}|^2 \Big) s \Big|^2 \tag{12}$$

where

$$\beta_T = \sqrt{\frac{\sigma^2_s}{\beta^\dagger + \sigma^2_{v_{r_T}}}}. \tag{13}$$

Here, $\beta^\dagger$ is defined as

$$\beta^\dagger = \sigma^2_s \prod_{i=T-1}^{1} \beta^2_i \prod_{k=T}^{1} \left(|\bar{h}_{m_k}|^2 + \sigma^2_{\phi_k} \right) + \sum_{t=2}^{T} \Big(\Big[\prod_{i=T-1}^{t-1} \beta^2_i \prod_{k=T}^{t} \left(|\bar{h}_{m_k}|^2 + \sigma^2_{\phi_k} \right) \Big] \sigma^2_{v_{r_{t-1}}} \Big) \tag{14}$$

when $N \geq 2$, and $\beta_T = \sqrt{\frac{\sigma^2_s}{\sigma^2_s |\bar{h}_{m_1}|^2 + \sigma^2_s \sigma^2_{\phi_1} + \sigma^2_{v_{r_1}}}}$ when $T = 1$, i.e., $\beta = \beta_1$.

From (8) to (12), the MRC detection of many special cases for the multihop AF wireless mobile network under channel uncertainty corresponding to only channel estimation error $\bar{h}_{m_1}$, i.e., $\sigma^2_{\phi_{m_i}} = 0$ and $\sigma^2_{\phi_{m_N}} = 0$, only channel estimation error $\bar{h}_{m_i}$, i.e., $\sigma^2_{\phi_{m_1}} = 0$ and $\sigma^2_{\phi_{m_N}} = 0$, or only channel estimation error $\bar{h}_{m_N}$, i.e., $\sigma^2_{\phi_{m_1}} = 0$ and $\sigma^2_{\phi_{m_i}} = 0$, can be obtained. In particular, depending on the number of hop of mobile relay node, many combined special cases for the multihop AF wireless mobile network under channel uncertainty corresponding to different locations of channel estimation errors can be obtained. In other words, both channel estimation errors $\bar{h}_{m_1}$ and $\bar{h}_{m_N}$ can be obtained. However, in this current paper, for simplicity and convenience, channel estimation error added to only one link between two nodes in entire network will be considered. Therefore, for only channel estimation error $\bar{h}_{m_1}$ when $\sigma^2_{\phi_{m_i}} = 0$ and $\sigma^2_{\phi_{m_N}} = 0$, the MRC detection at the destination node can be written as

$$\hat{s}^1_{D\text{–}AF} = \arg\min_{s \in \boldsymbol{A}_s} \Big| \gamma_T \Big(\prod_{i=2}^{N} h^*_{m_i} \Big) \bar{h}^*_{m_1} \hat{y}^1_{d\text{–}AF} - \gamma^2_T \Big(\prod_{i=2}^{N} |h_{m_i}|^2 \Big) |\bar{h}_{m_1}|^2 s - \gamma^2_T \Big(\prod_{i=2}^{N} |h_{m_i}|^2 \Big) |\phi_{m_1}|^2 s \Big|^2 \tag{15}$$

where

$$\gamma_T = \sqrt{\frac{\sigma^2_s}{\gamma^\dagger + \sigma^2_{v_{r_T}}}}. \tag{16}$$

Here, $\gamma^\dagger$ is defined as

$$\gamma^\dagger = \sigma^2_s \prod_{i=T-1}^{1} \gamma^2_i \prod_{k=T}^{2} |h_{m_k}|^2 |\bar{h}_{m_1}|^2 + \sum_{t=2}^{T} \Big(\Big[\prod_{i=T-1}^{t-1} \gamma^2_i \prod_{k=T}^{t} |h_{m_k}|^2 \Big] \sigma^2_{v_{r_{t-1}}} \Big) \tag{17}$$

when $T \geq 2$, and $\gamma = \sqrt{\frac{\sigma^2_s}{\sigma^2_s |\bar{h}_{m_1}|^2 + \sigma^2_s \sigma^2_{\phi_1} + \sigma^2_{v_{r_1}}}}$ when $T = 1$, i.e., $\gamma = \gamma_1$.

In addition, the MRC detection at the destination node for only channel estimation error $\bar{h}_{m_i}$ when $\sigma^2_{\phi_{m_1}} = \cdots = \sigma^2_{\phi_{m_{i-1}}} = 0$ and $\sigma^2_{\phi_{m_{i+1}}} = \cdots = \sigma^2_{\phi_{m_N}} = 0$ can be obtained as

$$\hat{s}^2_{D\text{–}AF} = \arg\min_{s \in \boldsymbol{A}_s} \Big| \delta_T \Big(\prod_{i=1, i \neq l}^{N} h^*_{m_i} \Big) \bar{h}^*_{m_l} \hat{y}^2_{d\text{–}AF} - \delta^2_T \Big(\prod_{i=1, i \neq l}^{N} |h_{m_i}|^2 \Big) |\bar{h}_{m_l}|^2 s - \delta^2_T \Big(\prod_{i=1, i \neq l}^{N} |h_{m_i}|^2 \Big) |\phi_{m_l}|^2 s \Big|^2 \tag{18}$$

where

$$\delta_T = \sqrt{\frac{\sigma^2_s}{\delta^\dagger_l + b_l + \sigma^2_{v_{r_T}}}} \tag{19}$$

due to the channel uncertainty of the l-th link, $|\bar{h}_{m_l}|$ should be used instead of $|h_{m_l}|^2$ if $i = l$. Here, $\delta^\dagger_l$ and b_l

are, respectively, defined when $T \geq 3$ and $2 \leq l \leq T-1$, as

$$\delta_l^{\dagger} = \sigma_s^2 \prod_{i=T-1}^{1} \delta_i^2 \prod_{k=T}^{l+1} |h_{m_k}|^2 \prod_{k=l-1}^{1} |h_{m_k}|^2 |\bar{h}_{m_l}|^2 + \sum_{t=2}^{T} \Big(\Big[\prod_{i=N-1}^{t-1} \delta_i^2 \prod_{k=T}^{l+1} |h_{m_k}|^2 \prod_{z=l-1}^{t} |h_{m_z}|^2 |\bar{h}_{m_l}|^2 \Big] \sigma_{v_{r_{t-1}}}^2 \Big) \quad (20)$$

and

$$b_l = \sigma_s^2 \prod_{i=T-1}^{1} \delta_i^2 \prod_{k=T}^{l+1} |h_{m_k}|^2 \prod_{z=l-1}^{1} |h_{m_z}|^2 \sigma_{\phi_{s_l}}^2 + \sum_{t=2}^{T-1} \Big(\Big[\prod_{i=T-1}^{t-1} \delta_i^2 \prod_{k=T}^{l+1} |h_{m_k}|^2 \prod_{z=l-1}^{t} |h_{m_z}|^g \sigma_{\phi_{s_l}}^2 \Big] \sigma_{v_{r_{t-1}}}^2 \Big) \quad (21)$$

where $g = 0$ if $t > z$, $g = 2$ if $t \leq z$, and $\delta = \sqrt{\frac{\sigma_s^2}{\sigma_s^2 |h_{m_1}|^2 + \sigma_{v_{r_1}}^2}}$ when $T = 1$, i.e., $\delta = \delta_1$.

Finally, the MRC detection at the destination node for only channel estimation error $\bar{h}_{m_N}$, when $\sigma_{\phi_{m_1}}^2 = 0$ and $\sigma_{\phi_{m_i}}^2 = 0$ can be represented as

$$\hat{s}_{D\text{–}AF}^3 = \arg\min_{s \in \boldsymbol{A}_s} \Big| \varepsilon_T \Big(\prod_{i=1}^{N-1} h_{m_i}^* \Big) \bar{h}_{m_N}^* \hat{y}_{d\text{–}AF}^3 - \varepsilon_T^2 \Big(\prod_{i=1}^{N-1} |h_{m_N}|^2 \Big) |\bar{h}_{m_N}|^2 s - \varepsilon_T^2 \Big(\prod_{i=1}^{N-1} |h_{m_N}|^2 \Big) |\phi_{m_N}|^2 s \Big|^2 \quad (22)$$

where

$$\varepsilon_T = \sqrt{\frac{\sigma_s^2}{\varepsilon^{\dagger} + \sigma_{v_{r_T}}^2}}. \quad (23)$$

Here, when $T \geq 2$, $\varepsilon^{\dagger}$ is defined as

$$\varepsilon^{\dagger} = \sigma_s^2 \prod_{i=T-1}^{1} \varepsilon_i^2 \prod_{k=T}^{1} |h_{m_k}|^2 + \sum_{t=2}^{T} \Big(\Big[\prod_{i=T-1}^{t-1} \varepsilon_i^2 \prod_{k=T}^{t} |h_{m_k}|^2 \Big] \sigma_{v_{r_{t-1}}}^2 \Big) \quad (24)$$

where $\varepsilon = \sqrt{\frac{\sigma_s^2}{\sigma_s^2 |h_{m_1}|^2 + \sigma_{v_{r_1}}^2}}$ when $T = 1$, i.e., $\varepsilon = \varepsilon_1$. The superscript 1, 2, and 3 in $\hat{s}_{D\text{–}AF}$ and $\hat{y}_{d\text{–}AF}$ stands for the case of channel uncertainty for only channel estimation error $\bar{h}_{m_1}$, only channel estimation error $\bar{h}_{m_i}$, and only channel estimation error $\bar{h}_{m_N}$, respectively.

C. DF Scheme under No Channel Uncertainty

A DF wireless mobile network under no channel uncertainty with one-source-one-destination mobile node pair and N-multihop mobile relay nodes is described in Fig. 1(c). A source node transmits a signal s to the first relay node during the first time slot, where R_0 in Fig. 1(c) is the source node. Then, the first relay node decodes and reencodes its received signal from the source node. After that, it forwards its reencoded data to the second relay during the second time slot. This procedure will be repeated until the last relay, where the relay nodes and destination node in Fig. 1(c) are represented by R_1 to R_{N-1}, and R_N, respectively.

Using the mobile-to-mobile channel, the received complex signal $y_{r_{1-DF}} \in \mathbf{C}^{1\times 1}$ at the first relay node under no channel uncertainty is written as

$$y_{r_{1\text{–}DF}} = h_{s_1} h_{r_1} s + v_{r_1} \quad (25)$$

where the subscript $_{DF}$ is the case of the DF wireless mobile network. Therefore, the original transmitted message s from the source node is optimally detected at the first relay node under no channel uncertainty using the MRC detection as

$$\hat{s}_{1\text{–}DF} = \arg\min_{s \in \boldsymbol{A}_s} \big| h_{s_1}^* h_{r_1}^* y_{r_{1\text{–}DF}} - |h_{s_1} h_{r_1}|^2 s \big|^2. \quad (26)$$

Then, the detected message $\hat{s}_{1\text{–}DF}$ at the first relay node is reencoded and consequently transmitted during the second time slot with the same average power P_s in [1]. Thus, the received complex signal $y_{r_{i\text{–}DF}} \in \mathbf{C}^{1\times 1}$ at the i-th relay node under no channel uncertainty is written as

$$y_{r_{i\text{–}DF}} = h_{s_i} h_{r_i} \hat{s}_{(i-1)\text{–}DF} + v_{r_i}. \quad (27)$$

After that, the original transmitted message s from the source node is optimally detected at the i-th relay node under no channel uncertainty using the MRC detection as

$$\hat{s}_{i\text{–}DF} = \arg\min_{s \in \boldsymbol{A}_s} \big| \eta_{r_i} h_{s_i}^* h_{r_i} y_{r_{i\text{–}DF}} - \eta_{r_i} |h_{s_i} h_{r_i}|^2 s \big|^2 \quad (28)$$

where

$$\eta_{r_i} = \min\Big(\frac{\min\left(|h_{s_1} h_{r_1}|^2, \ \cdots, \ |h_{s_{N-2}} h_{r_{N-2}}|^2\right)}{|h_{s_{N-1}} h_{r_{N-1}}|^2}, 1 \Big). \quad (29)$$

In (29), η_{r_i} is a power scaling constraint coefficient per hop. Namely, the power scaling coefficient is constrained as $0 < \eta_{r_i} \leq 1$ to adjust the power at the relay node and accomplish a better system performance at the destination node.

Similarly, the detected message $\hat{s}_{i\text{–}DF}$ at the i-th relay node is reencoded and transmitted during the $i+1$ time slots with the same average power P_s. Finally, during the N-th time slot, the corresponding received complex signal $y_{d\text{–}DF} \in \mathbf{C}^{1\times 1}$ at the destination node under no channel uncertainty can be written as

$$y_{d\text{–}DF} = h_{s_N} h_{r_N} \hat{s}_{N-1} + v_{r_N}. \quad (30)$$

Thus, the originally transmitted message s from the source node is detected at the destination node using the MRC detection as

$$\hat{s}_{D\text{–}DF} = \arg\min_{s \in \boldsymbol{A}_s} \big| \theta_{r_N} h_{s_N}^* h_{r_N}^* y_{r_{N\text{–}DF}} - \theta_{r_N} |h_{s_N} h_{r_N}|^2 s \big|^2 \quad (31)$$

where

$$\theta_{r_N} = \min\Big(\frac{\min(|h_{s_1}h_{r_1}|^2,\ \cdots,\ |h_{s_{N-1}}h_{r_{N-1}}|^2)}{|h_{s_N}h_{r_N}|^2}, 1\Big). \tag{32}$$

Like η_{r_i}, θ_{r_N} is a power scaling constraint coefficient at the destination node. In other words, the power scaling coefficient is constrained as $0 < \theta_{r_N} \leq 1$ to improve a system performance at the destination node.

D. DF Scheme under Channel Uncertainty

In practice, due to channel estimation errors, the estimates of the imperfect channel complex coefficient $\bar{h}_{t_1}$, $\bar{h}_{t_i}$, and $\bar{h}_{t_N}$ instead of $h_{t_1} \triangleq h_{s_1}h_{r_1}$, $h_{t_i} \triangleq h_{s_i}h_{r_i}$, and $h_{t_N} \triangleq h_{s_N}h_{r_N}$ should be, respectively, applied as

$$\bar{h}_{t_1} = h_{t_1} - \phi_{t_1} \tag{33}$$
$$\bar{h}_{t_i} = h_{t_i} - \phi_{t_i} \tag{34}$$
$$\bar{h}_{t_N} = h_{t_N} - \phi_{t_N} \tag{35}$$

where each channel estimation error ϕ_{t_1}, ϕ_{t_i}, and ϕ_{t_N} are complex i.i.d. cascaded Rayleigh fading channels. In addition, $v_{t_1}, \cdots, v_{t_N}$ are zero-mean CAWGN random variables with variance $\sigma^2_{v_{t_1}}, \cdots, \sigma^2_{v_{t_N}}$. Therefore, the received complex signal $\hat{y}_{t_1\text{–}DF}$ at the first relay node under channel uncertainty, $\hat{y}_{t_i\text{–}DF}$ at the i-th relay node under channel uncertainty, and $\hat{y}_{d\text{–}DF}$ at the destination node under channel uncertainty are, respectively, written as

$$\hat{y}_{t_1\text{–}DF} = \bar{h}_{t_1}s + \phi_{t_1}s + v_{t_1} \tag{36}$$
$$\hat{y}_{t_i\text{–}DF} = \bar{h}_{t_i}\hat{s}_{(i-1)\text{–}DF} + \phi_{t_i}\hat{s}_{(i-1)\text{–}DF} + v_{t_i} \tag{37}$$

and

$$\hat{y}_{d\text{–}DF} = \bar{h}_{t_N}\hat{s}_{(N-1)\text{–}DF} + \phi_{t_N}\hat{s}_{(N-1)\text{–}DF} + v_{t_N} \tag{38}$$

where the superscript *hat* ($\hat{}$) in $y_{t_1\text{–}DF}$, $y_{t_i\text{–}DF}$, and $y_{d\text{–}DF}$ is the case of the DF wireless mobile network under channel uncertainty. Accordingly, the original transmitted message s from the source node is optimally detected at the first relay node under channel uncertainty, at the i-th relay node under channel uncertainty, and at the destination node under channel uncertainty using the MRC detection, respectively, as

$$\hat{s}_{1\text{–}DF} = \arg\min_{s\in\boldsymbol{A}_s} \left|\bar{h}^*_{t_1}\hat{y}_{t_1\text{–}DF} - |\bar{h}_{t_1}|^2 s - |\phi_{t_1}|^2 s\right|^2 \tag{39}$$
$$\hat{s}_{i\text{–}DF} = \arg\min_{s\in\boldsymbol{A}_s} \left|\vartheta_{t_i}\bar{h}^*_{t_i}\hat{y}_{t_i\text{–}DF} - \vartheta_{t_i}|\bar{h}_{t_i}|^2 s - \lambda_{t_i}|\phi_{t_i}|^2 s\right|^2 \tag{40}$$

and

$$\hat{s}_{D\text{–}DF} = \arg\min_{s\in\boldsymbol{A}_s} \big|\mu_{t_N}\bar{h}^*_{t_N}\hat{y}_{d_{N-DF}} - \mu_{t_N}|\bar{h}_{t_N}|^2 s - \xi_{t_N}|\phi_{t_N}|^2 s\big|^2 \tag{41}$$

where

$$\vartheta_{t_i} = \min\Big(\frac{\min(|\bar{h}_{t_1}|^2,\ \cdots,\ |\bar{h}_{t_{N-2}}|^2)}{|\bar{h}_{t_{N-1}}|^2}, 1\Big) \tag{42}$$

$$\lambda_{t_i} = \min\Big(\frac{\min(|\phi_{t_1}|^2,\ \cdots,\ |\phi_{t_{N-2}}|^2)}{|\phi_{t_{N-1}}|^2}, 1\Big) \tag{43}$$

$$\mu_{t_N} = \min\Big(\frac{\min(|\bar{h}_{t_1}|^2,\ \cdots,\ |\bar{h}_{t_{N-1}}|^2)}{|\bar{h}_{t_N}|^2}, 1\Big) \tag{44}$$

$$\xi_{t_N} = \min\Big(\frac{\min(|\phi_{t_1}|^2,\ \cdots,\ |\phi_{t_{N-1}}|^2)}{|\phi_{t_N}|^2}, 1\Big). \tag{45}$$

And, ϑ_{t_i}, λ_{t_i}, μ_{t_N}, and ξ_{t_N} are, respectively, power scaling constraint coefficients at the relay and the destination nodes to enhance a system performance at the destination node. They are constrained as $\{\vartheta_{t_i},\ \lambda_{t_i},\ \mu_{t_N},\ \xi_{t_N}\} \in [0, 1)$.

From (33) to (38), as in the case of the multihop AF wireless mobile network under channel uncertainty, the MRC detection of many special cases for the multihop DF wireless mobile network under channel uncertainty corresponding to only channel estimation error $\bar{h}_{t_1}$, i.e., $\sigma^2_{\phi_{t_i}} = 0$ and $\sigma^2_{\phi_{t_N}} = 0$, only channel estimation error $\bar{h}_{t_i}$, i.e., $\sigma^2_{\phi_{t_1}} = 0$ and $\sigma^2_{\phi_{t_N}} = 0$, or only channel estimation error $\bar{h}_{t_N}$, i.e., $\sigma^2_{\phi_{t_1}} = 0$ and $\sigma^2_{\phi_{t_i}} = 0$, can be obtained.

Thus, for only channel estimation error $\bar{h}_{t_1}$ when $\sigma^2_{\phi_{t_i}} = 0$ and $\sigma^2_{\phi_{t_N}} = 0$, the MRC detection at the first relay node, each relay node, and the destination node can be, respectively, written as

$$\hat{s}^1_{1\text{–}DF} = \arg\min_{s\in\boldsymbol{A}_s} \left|\bar{h}^*_{t_1}\hat{y}^1_{t_1\text{–}DF} - |\bar{h}_{t_1}|^2 s - |\phi_{t_1}|^2 s\right|^2 \tag{46}$$
$$\hat{s}^1_{i\text{–}DF} = \arg\min_{s\in\boldsymbol{A}_s} \left|\rho_{t_i}h^*_{t_i}\hat{y}^1_{t_i\text{–}DF} - \rho_{t_i}|h_{t_i}|^2 s\right|^2 \tag{47}$$
$$\hat{s}^1_{D\text{–}DF} = \arg\min_{s\in\boldsymbol{A}_s} \left|\varpi_{t_N}h^*_{t_N}\hat{y}^1_{t_{N\text{–}DF}} - \varpi_{t_N}|h_{t_N}|^2 s\right|^2 \tag{48}$$

where

$$\rho_{t_i} = \min\Big(\frac{\min(|\bar{h}_{t_1}|^2, |h_{t_2}|^2,\ \cdots,\ |h_{t_{N-2}}|^2)}{|h_{t_{N-1}}|^2}, 1\Big) \tag{49}$$

$$\varpi_{t_N} = \min\Big(\frac{\min(|\bar{h}_{t_1}|^2, |h_{t_2}|^2,\ \cdots,\ |h_{t_{N-1}}|^2)}{|h_{t_N}|^2}, 1\Big). \tag{50}$$

In addition, for only channel estimation error $\bar{h}_{t_i}$ when $\sigma^2_{\phi_{t_1}} = 0$ and $\sigma^2_{\phi_{t_N}} = 0$, the MRC detection at the first relay node, each relay node, and the destination node can be, respectively, written as

$$\hat{s}^2_{1\text{–}DF} = \arg\min_{s\in \boldsymbol{A}_s} \left|h^*_{t_1}\hat{y}^2_{t_{1\text{–}DF}} - |h_{t_1}|^2 s\right|^2 \quad (51)$$

$$\hat{s}^2_{i\text{–}DF} = \arg\min_{s\in \boldsymbol{A}_s} \left|\tau^2_{t_i}\bar{h}^*_{t_i}\hat{y}^2_{t_{i\text{–}DF}} - \tau_{t_i}|\bar{h}_{t_i}|^2 s - |\phi_{t_i}|^2 s\right|^2 \quad (52)$$

$$\hat{s}^2_{D\text{–}DF} = \arg\min_{s\in \boldsymbol{A}_s} \left|\psi_{t_N} h^*_{t_N}\hat{y}^2_{t_{N\text{–}DF}} - \psi_{t_N}|h_{t_N}|^2 s|^2 s\right|^2 \quad (53)$$

where

$$\tau_{t_i} = \min\left(\frac{\min(|h_{t_1}|^2, \cdots, |h_{t_{i-1}}|^2, \varphi_t)}{|h_{t_{N-1}}|^2}, 1\right) \quad (54)$$

$$\varphi_t = \min\left(|\bar{h}_{t_i}|^2, |h_{t_{i+1}}|^2, \cdots, |h_{t_{N-2}}|\right) \quad (55)$$

$$\psi_{t_N} = \min\left(\frac{\min\left(|h_{t_1}|^2, |\bar{h}_{t_1}|^2, \cdots, |\bar{h}_{t_{N-1}}|^2\right)}{|\bar{h}_{t_N}|^2}, 1\right). \quad (56)$$

Finally, for only channel estimation error $\bar{h}_{t_N}$, when $\sigma^2_{\phi_{t_1}} = 0$ and $\sigma^2_{\phi_{t_i}} = 0$, the MRC detection at the first relay node, each relay node, and the destination node can be, respectively, written as

$$\hat{s}^3_{1\text{–}DF} = \arg\min_{s\in \boldsymbol{A}_s} \left|h^*_{t_1}\hat{y}^3_{t_{1\text{–}DF}} - |h_{t_1}|^2 s\right|^2 \quad (57)$$

$$\hat{s}^3_{i\text{–}DF} = \arg\min_{s\in \boldsymbol{A}_s} \left|\omega_{t_i} h^*_{t_i}\hat{y}^3_{t_{i\text{–}DF}} - \omega_{t_i}|h_{t_i}|^2 s\right|^2 \quad (58)$$

$$\hat{s}^3_{D\text{–}DF} = \arg\min_{s\in \boldsymbol{A}_s} \left|\nu_{t_N}\bar{h}^*_{t_N}\hat{y}^3_{t_{N\text{–}DF}} - \nu_{t_N}|\bar{h}_{t_N}|^2 s - |\phi_{t_N}|^2 s\right|^2 \quad (59)$$

where

$$\omega_{t_i} = \min\left(\frac{\min\left(|h_{t_1}|^2, \cdots, |h_{t_{N-2}}|^2\right)}{|h_{t_{N-1}}|^2}, 1\right) \quad (60)$$

$$\nu_{t_N} = \min\left(\frac{\min\left(|h_{t_1}|^2, \cdots, |h_{t_{N-1}}|^2\right)}{|\bar{h}_{t_N}|^2}, 1\right) \quad (61)$$

where the superscript 1, 2, and 3 in $\hat{s}_{1\text{–}DF}$, $\hat{s}_{i\text{–}DF}$, $\hat{s}_{D\text{–}DF}$, $\hat{y}_{t_{1\text{–}DF}}$, $\hat{y}_{t_{i\text{–}DF}}$, and $\hat{y}_{t_{N\text{–}DF}}$ stands for the case of channel uncertainty for only channel estimation error $\bar{h}_{t_1}$, only channel estimation error $\bar{h}_{t_i}$, and only channel estimation error $\bar{h}_{t_N}$, respectively. Additionally, ρ_{t_i}, ϖ_{t_N}, τ_{t_i}, ψ_{t_N}, ω_{t_i}, and ν_{t_N} are power scaling constraint coefficients at the relay and the destination nodes to improve a system performance at the destination node, respectively. They are constrained as $\{\rho_{t_i}, \varpi_{t_N}, \tau_{t_i}, \psi_{t_N}, \omega_{t_i}, \nu_{t_N}\} \in [0, 1)$.

III. Simulation Results

To evaluate the BER performance of the distributed AF and DE wireless mobile system under channel uncertainty, Monte-Carlo simulations were performed. All simulations were applied for mobile and fixed one-source-one-destination pair with 2, 3 relay nodes. All nodes are assumed to have only one antenna and the same noise power. The originally transmitted message from the source node was modulated using four-ary quadrature amplitude modulation with unit power. All perfect complex channel coefficients were generated using cascaded Rayleigh fading channels with zero-mean and unit variance.

2.5%, 5%, and 10%, of channel uncertainty are generated as cascaded Rayleigh fading channels with zero-mean and unit variance. In other words, the channel estimation error powers were chosen to satisfy $10\log_{10}(\sigma^2_{\phi_{m_1}}/\sigma^2_{\bar{h}_{m_1}}) = 10\log_{10}(\sigma^2_{\phi_{m_i}}/\sigma^2_{\bar{h}_{m_i}}) = 10\log_{10}(\sigma^2_{\phi_{m_N}}/\sigma^2_{\bar{h}_{m_N}}) = -16$ dB, -13 dB, and -10 dB for an AF wireless mobile network, while $10\log_{10}(\sigma^2_{\phi_{t_1}}/\sigma^2_{\bar{h}_{t_1}}) = 10\log_{10}(\sigma^2_{\phi_{t_i}}/\sigma^2_{\bar{h}_{t_i}}) = 10\log_{10}(\sigma^2_{\phi_{t_N}}/\sigma^2_{\bar{h}_{t_N}}) = -16$ dB, -13 dB, and -10 dB for a DF wireless mobile network. The simulation results with perfect channel state information, i.e., $\sigma^2_{\phi_{m_1}} = \sigma^2_{\phi_{m_i}} = \sigma^2_{\phi_{m_N}} = \sigma^2_{\phi_{t_1}} = \sigma^2_{\phi_{t_i}} = \sigma^2_{\phi_{t_N}} = 0$, are also included.

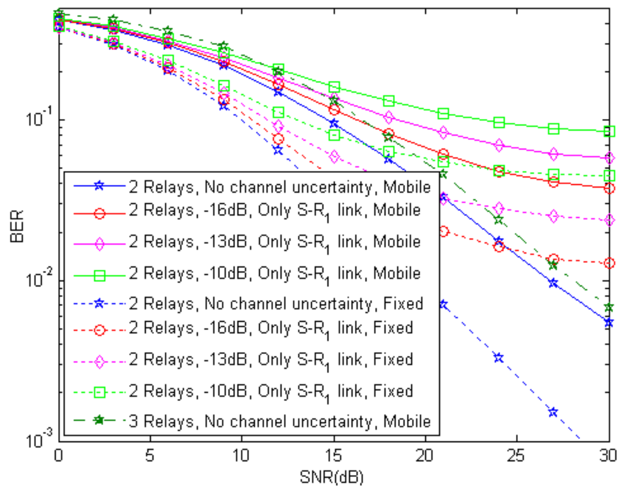

Fig. 2. BER performance of an AF wireless network under channel uncertainty for only one link, i.e., source-relay, using imperfect channels ($\bar{h}_{m_1}$, h_{m_i}, h_{m_N}) with mobile and fixed communication nodes for 2 and 3 relays.

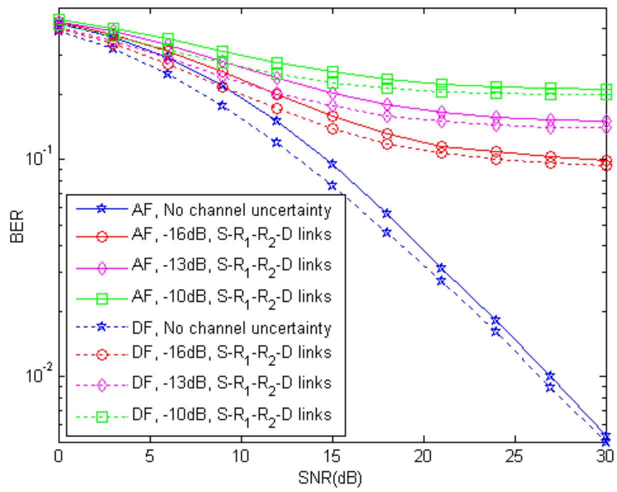

Fig. 3. BER performance of AF and DF wireless mobile networks under both no channel uncertainty and channel uncertainty in all links of the entire network using imperfect channels with 2 relays.

Figure 2 presents BER performance of an AF wireless mobile network under no channel uncertainty and channel uncertainty for only one link (source-relay) using imperfect complex channels $(\bar{h}_{m_1}, h_{m_i}, h_{m_N})$ between source, 2 or 3 relays and destination. Both fixed and mobile cases are shown. For wireless mobile network, it is observed that increasing the number of the relay node results in a worse BER performance. Wireless network with mobile nodes shows worse BER performance compared to wireless network with fixed ones. It is also observed that increasing the power of imperfect channel complex coefficients degrades the BER performance.

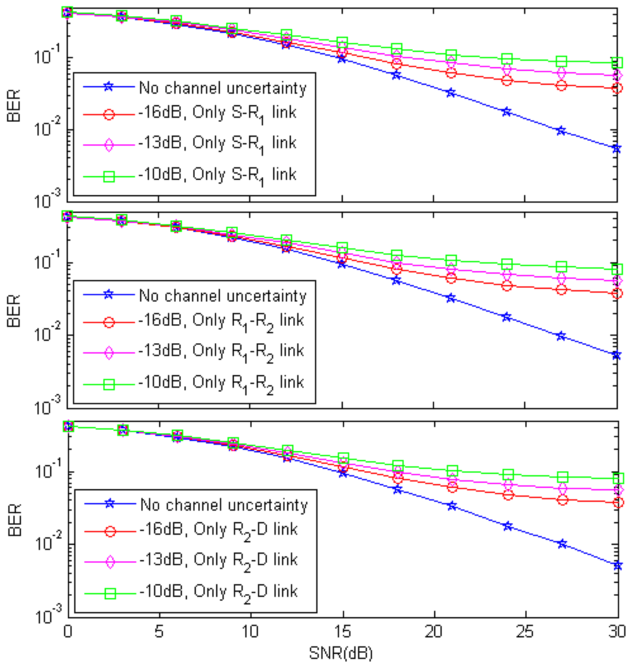

Fig. 4. BER performance of AF wireless mobile networks under channel uncertainty for only source-relay, only relay-relay, or only relay-destination link using imperfect channels $(\bar{h}_{m_1}, h_{m_i}, h_{m_N})$, $(h_{m_1}, \bar{h}_{m_i}, h_{m_N})$, or $(h_{m_1}, h_{m_i}, \bar{h}_{m_N})$ with 2 relays.

Figure 3 shows BER performance of AF and DF wireless mobile networks under both no channel uncertainty and channel uncertainty in all links with 2 relays. As shown in Fig. 3, due to imperfect channel complex coefficients in all links, the worst BER performance is observed compared to other AF and DF special cases. It is also found that DF performs better than AF in a mobile scenario because the noise in an AF mobile scenario builds up with each data transmission.

Figure 4 and 7 show BER performance of AF and DF wireless mobile network under channel uncertainty for only source-relay, only relay-relay, and only relay-destination link with 2 relays, respectively. As in the case of Fig. 3, it is observed that BER gets worse as the variances of imperfect channel complex coefficients increases. It is also observed that BER performance of both AF and DF channel uncertainty case in only one link is almost the same regardless of the link locations.

Figure 5 and 8 provide BER performance of AF and DF wireless mobile networks under channel uncertainty for only one link (source-relay), and two links (source-relay and relay-destination) with 2 relays, respectively. It is also observed in Fig. 5 and 8 that BER for channel uncertainty in two links gets worse as the variances of imperfect channel complex coefficients increase. In addition, it is found that BER performance under channel uncertainty for only one link becomes better compared to the case of imperfect channel complex coefficients of two links.

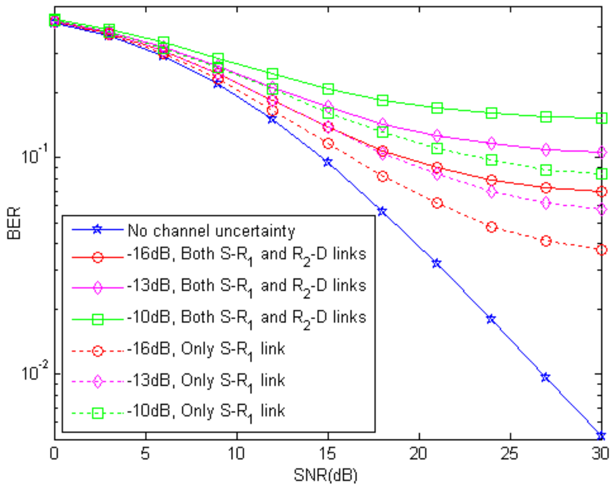

Fig. 5. BER performance of AF wireless mobile networks under channel uncertainty for only one link i.e., source-relay, and two links, i.e., source-relay and relay-destination, using imperfect channels $(\bar{h}_{m_1}, h_{m_i}, h_{m_N})$ and $(\bar{h}_{m_1}, h_{m_i}, \bar{h}_{m_N})$ with 2 relays.

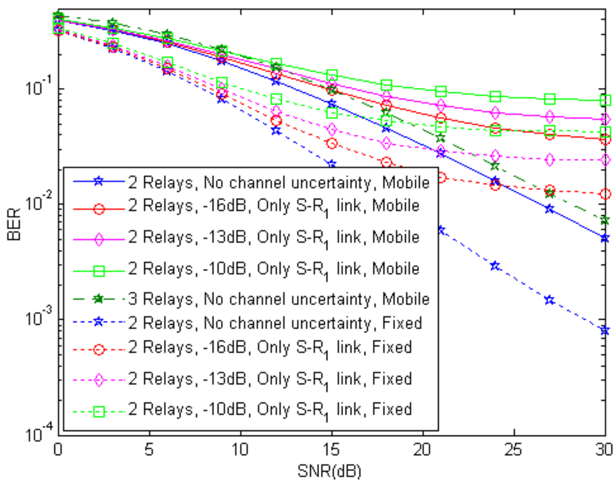

Fig. 6. BER performance of DF wireless network under channel uncertainty for only one link, i.e., source-relay, using imperfect channels $(\bar{h}_{t_1}, h_{t_i}, h_{t_N})$ with mobile and fixed communication nodes for 2 and 3 relays.

Figure 6 presents BER performance of DF wireless network under channel uncertainty for only one link (source-relay) using imperfect channels $(\bar{h}_{t_1}, h_{t_i}, h_{t_N})$ with 2 and 3 relays. For wireless mobile network, it is observed that increasing the number of the relay node results in a worse BER performance. Similar to the case of AF wireless mobile network, the fixed case in DF performs better than mobile case.

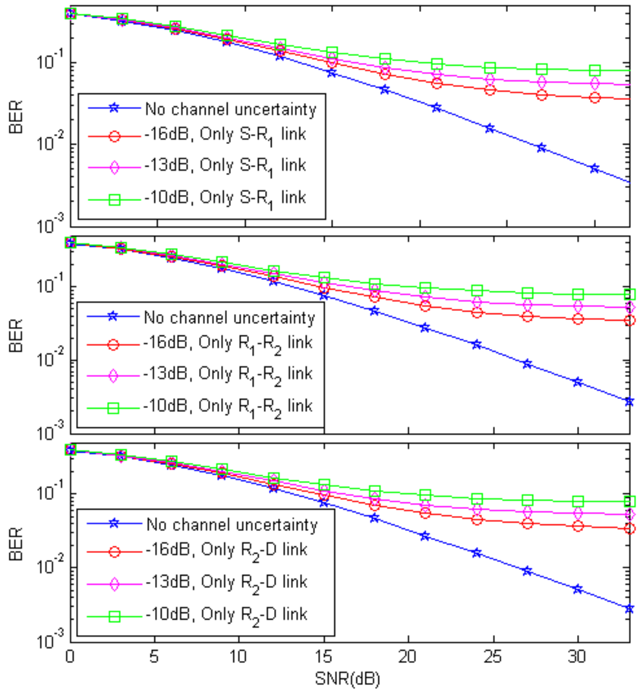

Fig. 7. BER performance of DF wireless mobile network under channel uncertainty for only source-relay, only relay-relay, or only relay-destination link using imperfect channels $(\bar{h}_{t_1}, h_{t_i}, h_{t_N})$, $(h_{t_1}, \bar{h}_{t_i}, h_{t_N})$, or $(h_{t_1}, h_{t_i}, \bar{h}_{t_N})$ with 2 relays.

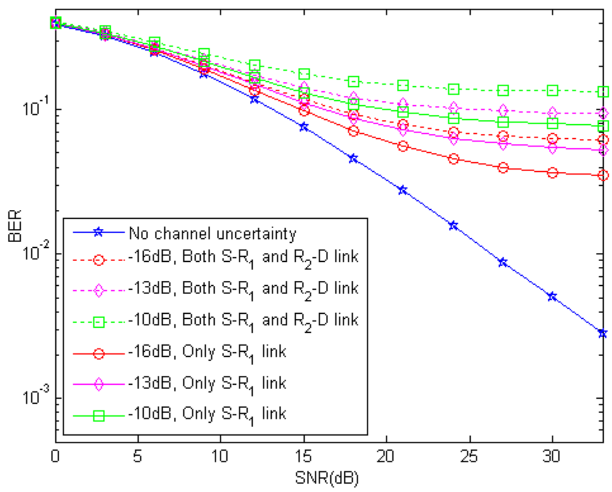

Fig. 8. BER performance of DF wireless mobile network under channel uncertainty for only one link i.e., source-relay, and two links, i.e., source-relay and relay-destination, using imperfect channels $(\bar{h}_{t_1}, h_{t_i}, h_{t_N})$ and $(\bar{h}_{t_1}, h_{t_i}, \bar{h}_{t_N})$ with 2 relays.

IV. Conclusion

This paper studied both nonregenerative AF and regenerative DF wireless mobile relay networks under both no channel uncertainty and channel uncertainty. A wireless network consisting of a one-source-one-destination mobile pair and N-multihop mobile relay nodes without the source-destination direct path was investigated. New MRC-based detectors were proposed and applied at the relays and the destination to optimally detect the original transmitted message from the source node.

It was observed that diversity can be lost by increasing the channel estimation errors power. In addition, it was shown that BER gets worse as the number of hops increase. It was observed that the worst performance was occurred when channel uncertainty occurs in all network links. While less degradation was observed when channel uncertainty occurred in source-relay, relay-relay, or relay-destination links only. These different cases were investigated separately and as a whole in this paper.

It was also observed that the higher the number of links between hops that experienced channel uncertainty, the worse the BER performance. Finally, when channel uncertainty occurred in one link only, it was observed that the performance of the system was almost equivalent regardless the link location. In other words, BER performance for the multihop wireless system with channel uncertainty depends on both the number of hops and channel estimation errors power.

References

[1] K. J. Ray Liu, A. K. Sadek, W. Su, and A. Kwasinski, *Cooperative communications and networking*. 1st ed., Cambridge, NY: Cambridge University Press, 2009.

[2] Y. W. Hong, W. J. Huang, F. H. Chiu, and C. C. J. Kuo, "Cooperative communications in resource-constrained wireless networks," *IEEE Signal Process. Mag.*, vol. 24, no. 3, pp. 47-57, May 2007.

[3] A. Saadani and O. Traoré, "Orthogonal or non-orthogonal amplify and forward protocol: How to cooperate?," *IEEE WCNC 2008*, Las Vegas, NV, Mar. 2008, pp 368-373.

[4] J. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behaviour," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[5] S. Lee and S. Chung, "When is compress-and-forward optimal?," *IEEE ITA 2010*, San Diego, CA, Jan. 2010.

[6] G. Kramer, M. Gastpar, and P. Gupta, "Cooperative strategies and capacity theorems for relay networks," *IEEE Transactions on Information Theory*, vol. 51, no. 9, pp. 3037-3063, Sep. 2005.

[7] S. Berger and A. Wittneben, "Cooperative distributed multiuser MMSE relaying in wireless ad-hoc networks," *IEEE 39th Asilomar Conference*, Oct. 2005, pp. 1072-1076.

[8] N. Khajehnouri and A. H. Sayed, "Distributed MMSE relay strategies for wireless sensor networks," *IEEE Transactions on Signal Processing*, vol. 55, no. 7, Jul. 2007.

[9] S. Berger and A. Wittneben, "Cooperative distributed multiuser MMSE relaying in wireless ad-hoc networks," *IEEE 39th Asilomar Conf.*, Oct. 2005, pp. 1072-1076.

[10] R. Krishna, Z. Xiong, and S. Lambotharan, "A cooperative MMSE relay strategy for wireless sensor networks," *IEEE Signal Processing Letters*, vol. 15, pp. 549-552, 2008.

[11] T. Wang, A. Cano, G. B. Giannakis, and J. Laneman, "High-performance cooperative demodulation with decode-and-forward relays," *IEEE Transactions on Communications*, vol. 55, no. 7, pp. 1427-1438, July 2007.

[12] T. Wang, G. B. Giannakis, and R. Wang, "Smart regenerative relays for link-adaptive cooperative communications," *IEEE Transactions on Communications*, vol. 56, no. 11, pp. 1950-2008, Nov. 2008.

[13] T. Wang and G. B. Giannakis, "Complex field network coding for multiuser cooperative communications," *IEEE Transactions on Communications*, vol. 26, no. 3, pp. 561-571, April 2008.

[14] J. Joung and A. H. Sayed, "Power allocation for beamforming relay networks under channel uncertainties," *IEEE GLOBECOM*, Honolulu, HI, Nov. 2007.

[15] Y. Ibdah, H. M. Kwon, K. Lee, Z. Wang, Y. Bi, and M. Jo, "Broadband jamming and channel uncertainty for noncooperative wireless relay networks under received power constraint," *IEEE AMS 2011*, Manila, Philippines, May 23-27, 2011.
[16] K. Lee, H. M. Kwon, Y. Ding, Z. Wang, Y. Bi, and Y. Ibdah, "Amplifying matrix design for cooperative relay networks under channel uncertainty and power constraint," *ICWMC 2011*, Luxembourg, June 19-24, 2011.
[17] S. Amara and H. Boujemaa, "Multihop Multibranch DF Relaying For Cooperative Systems," *VTC Spring 2011*, pp. 1-5, Hungary. May 2011
[18] J. Boyer, D. D. Falconer, and H. Yanikomeroglu, "Multihop diversity in wireless relaying channels," *IEEE Transactions on communications*, vol. 52, no. 10, pp. 1820-1830, Oct. 2004.
[19] H. Mazen and A. Mohamed-Slim, "A Performance Study of Dual-Hop Transmissions With Fixed Gain Relays," *IEEE Transactions on Wireless Communications*, vol. 3, no. 6, Nov. 2004.
[20] G. Farhadi and N. C. Beaulieu, "On the performance of amplify-and-forward cooperative systems with fixed gain relays," *IEEE Transactions on Wireless Communications*, vol. 7, no. 5, pp. 1851-1856, 2008.
[21] W. Muenthetrakoon, K. Khutwiang, C. Kotchasarn, "SER of Multi-Hop Decode and Forward Cooperative Communications under Rayleigh Fading Channel," *ISMS 2011*, pp. 318-323, Malaysia & Cambodia, Jan 2011.
[22] Q. B. V. Nguyen, and K. Y. Hyun, "Error probability performance for multi-hop decode-and-forward relaying over Rayleigh fading channels," *ICACT 2009*, vol. 3, pp. 1512-1516, Korea, Feb. 2009.
[23] G. Amarasuriya, C. Tellambura, M. Ardakani, "New Performance Approximations for Multi-Hop Fixed-gain AF Relay Networks,", *ICC 2011*, pp.1-5, Kyoto, Japan, June 2011.
[24] Z. Xiaojuan and G. Yi, "Adaptive Power Allocation for Multi-hop OFDM Relaying Systems", *ICICS 2007*, pp. 1-5, Singapore, Dec. 2007.
[25] Z. Xiaojuan and G. Yi, "Adaptive Power Allocation for Multi-Hop Regenerative Relaying OFDM Systems", *ICSPCS 2010*, pp. 1-5, Australia, Dec. 2010
[26] C. Patel, G. Stuber, and T. Pratt, "Simulation of Rayleigh-faded mobile-to-mobile communication channels," *IEEE Transactions on Communications*, vol. 53, pp. 1876-1884, Nov. 2005.
[27] Kovacs, P. Eggers, K. Olesen, and L. Patersen, "Investigations of outdoor-to-indoor mobile-to-mobile radio communication channels," *VTC 2002*, Vancouver, BC, CA, vol. 1, pp. 430-434, May 2002.
[28] Y. Ibdah, Y. Ding, H. M. Kwon, and K. Lee, "Simulations on the Statistical Properties for Cascaded Rayleigh Fading Channel," *MILCOM 2011*, pp.1-6, Maryland, Nov. 2011.
[29] J. Maurer, T. Fugen, and W. Wiesbeck, "Narrow-band measurement and analysis of the inter-vehicle transmission channel at 5.2 GHz," *VTC 2002*, vol. 3, pp. 1274-1278, May 2002.
[30] V. Erceg, S. Fortune, J. Ling, A. Rustako, and R. Valenzuela, "Comparisons of a computer-based propagation prediction tool with experimental data collected in urban microcellular environments," *IEEE J. Sel. Areas Communication*, vol. 15, no. 4, May 1997.

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