Capacity Analysis of Broadband Relaying Systems for Low-Voltage Powerline Communications

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Abstract —Low-Voltage Powerline Communications (LV PLC) is a favorable information exchange scheme for many Smart Grid (SG) applications. In this paper we focus on the broadband dual-hop relaying systems over LV PLC channel in which the relay node operates in either Amplify-and-Forward (AF) or Decode-and-Forward (DF) relaying protocol. The closed-form expressions of capacities for non-cooperative and cooperative relaying systems are derived. Numerical simulations reveal the performances in AF and DF modes in terms of the system capacity, which are complying with Electromagnetic Compatibility (EMC) regulations in the United States, European Union and Germany respectively. It's shown that relaying LV PLC systems can obtain significant capacity improvement compared with Direct Transmission (DT) when the transmission distance is greater than a certain threshold. In addition, the effect of the relay locations to the relaying system capacity is analyzed in this paper.

Index Terms—System capacity, relaying protocol, low-voltage powerline communications, electromagnetic compatibility

I. Introduction

Powerline communication (PLC) which transmits data over widely power distribution networks can support many Smart Grid (SG) services such as the networking of consumers' home appliances, automated devices and information about the power grid conditions [1]. Furthermore, it provides a convenient and cost-effective communication medium since the power distribution networks are already ubiquitous and almost cover every inhabited area. This will reduce the deployment costs significantly since it does not need building extra cabling as in most traditional wire-line or wireless communication infrastructures [2]. The communication via powerlines can reach anywhere powerlines exist, especially places where radio signal cannot propagate through, e.g., underwater, underground, and rooms with metal walls. Intensive studies regarding Medium-Voltage (MV) PLC [3]-[5] have been conducted, and LV PLC networks have got increasingly attentions [6], [7].

However, PLC in practice will also face several major challenges which are caused by realistic adverse conditions in power lines. Harsh attenuation which varies with the powerline conductor type, the network topology, the connected electrical loads, frequency as well as transmission distance is one of those major challenges. Furthermore, powerline cables are sensitive to external noises due to without electromagnetic shielding, while the sources of the noises in the powerline networks are very complex, including synchronous and asynchronous impulse noises, narrowband interferences, and colored background noises [8]. In addition, to avoid interference with the other systems, the PLC transmitted power is limited by the EMC regulations [9], [10] which are commonly very low values. The above factors seriously affect the quality of data transmission.

Most SG applications require reliable and high data rate communications with broad coverage. However, conventional PLC systems are challenged by reliability and capacity due to low transmit power, limited bandwidth and harsh channel conditions. Relaying protocols, which have been widely utilized in wireless networks to increase system capacity and link reliability [11], [12], have been considered in powerline networks. In [2], the two-hop relaying PLC system capacity was analyzed from the viewpoint of information theory and the capacity benefits were demonstrated using two PLC channel models, i.e., the signal attenuation model and the transmission line model while only AF mode was considered. In [5], a multi-hop OFDM-based AF relaying protocol for MV broadband PLC system was proposed and a closed-form expression of the system capacity was derived. In [7], the Opportunistic Decode-and-Forward (ODF) protocol was proposed over In-Home PLC systems. In [13], system capacities were obtained for OFDM-based relay-aided two hop MV PLC networks and AF mode and DF mode were both considered. In [14], system capacities for indoor, LV, and MV broadband transmission systems were analyzed using deterministic broadband PLC channels with the characteristics of noise while only capacity in DT mode was discussed, capacities in relay-aided transmission modes were not analyzed. It's noted that the capacity features of dual-hop cooperative relaying systems over LV broadband PLC networks have not been fully investigated.

In this paper, system capacities are analyzed for dual-hop relaying systems over LV PLC channel. Our main contributions are summarized as follows.

- We adopt a time-division relaying protocol for LV PLC network which is different from the cooperative relaying protocol in [13]. In the protocol of this paper,

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only the relay node transmits signal to the destination node in the second time slot while the source node keeps silent. It avoids the destination node receiving information simultaneously from multiple nodes and saves power because the source node transmit signal only in the first time slot.

- The closed-form expressions of capacities for relaying systems using either AF or DF protocols are derived and the comparisons of system capacities in different protocol are presented for LV PLC systems.
- The EMC regulations in different regions for LV PLC networks are summarized and the effects to relay-aided dual-hop LV PLC system capacities are revealed.

The remainder of this paper is organized as follows. In Section II, the signal models for dual-hop relaying broadband LV PLC systems are presented and the closed-form expressions of the system capacities are derived in Section III. The effect of EMC regulations for LV PLC system capacity is presented in Section IV and the numerical results are analyzed in Section V. Finally conclusions are drawn in Section VI.

II. LV PLC Channel and Noise Model

In this section, we describe the channel and noise model of LV power grids using the multipath model which adopts top-bottom approach.

A. *Channel Model*

The multipath model is obtained based on real channel measurement, and the parameters of path, e.g., delay and attenuation, are estimated using the least square fitting algorithm. In the multipath model, signal propagation in the powerline is described as being dominated by multiple paths caused by various powerline branches and impedance mismatch. The signal attenuation model is a special multiple model which is widely considered by related literature due to its simplicity. It only considers the dominant path which is the basic attenuation characteristic of the LV powerline channel while omitting other paths [6]. So in this paper, we use the signal attenuation model for simulations in this paper.

The frequency response $H(f,d)$ of a LV powerline link with length d can be approximated as

$$|H(f,d)| = e^{-(a_0 + a_1 f^k)d} \tag{1}$$

where k is the attenuation factor with typical value between 0.5 and 1; a_0 and a_1 are constants depending on the system configuration; f is in MHz.

We adopt the following experimental values for the signal attenuation model following [6]: $a_0 = 9.33 \cdot 10^{-3}$ and $a_1 = 5.1 \cdot 10^{-3}$, which are measured from German LV power distribution networks. We consider broadband LV PLC systems in the frequency band from 2 MHz to 20 MHz.

Fig. 1 plots the frequency response in LV PLC networks with the above parameters. We can observe clearly that along with the frequency goes up, the channel attenuation becomes stronger and along with the distance increases, the channel attenuation becomes stronger as well.

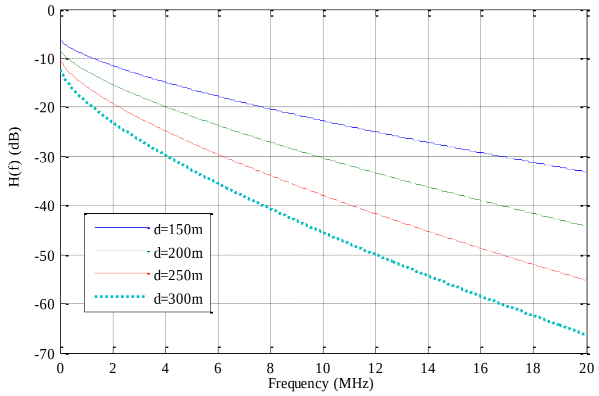

Fig. 1. Channel attenuation on the LV power grid.

B. *Noise Model*

The noise Power Spectral Density (PSD) can be modeled by a first-order exponential function as

$$10\log_{10} N(f) = N_0 + N_1 e^{-f/f_0} \, (\text{dBmW/Hz}) \tag{2}$$

Based on the measurement of the LV PLC networks [15], we adopt $N_0 = -125$, $N_1 = 35$ and $f_0 = 3.6$ for the residential environment, f is in MHz.

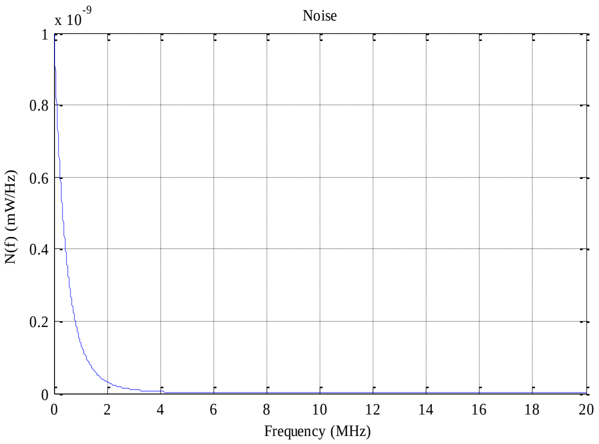

Fig. 2. The noise PSD in LV PLC channel

The noise PSD characteristics of LV PLC channel in the frequency range up to 20MHz is depicted in Fig. 2. It can be seen that the influence of the noise is more noticeable in the low frequency part.

III. System Model

In this section, the signal models for dual-hop relaying broadband LV PLC systems with non-cooperative and cooperative modes are presented, respectively. Base on the signal models, the corresponding closed-form expressions of system capacities in AF and DF mode are derived.

The broadband dual-hop non-cooperative and cooperative relaying systems are made up of one source node *s*, one destination node *d* and one relay node *r* which is shown in Fig. 3. The relay node is located between the source node and the destination node to assist the transmission from the source node to the destination node. We assume that each node employs half-duplex that can avoid the transmitted signals interfering with the received signals, since a terminal's transmitted signals are *100-150dB* above its received signals typically.

As shown in Fig. 3, the LV PLC systems adopt a time-division cooperative relaying protocol which is different from the cooperative relaying protocol in [13]. In the first time slot, the source node transmits signals to the relay node and the destination node. In the second time slot, the relay node deals with the received signals from the source node appropriately, then retransmits signals to the destination node while the source node keeps silence. It avoids the destination node receiving information simultaneously from multiple nodes and saves power because the source node transmits signal only in the first time slot. The destination node combines the signals received from both the source node in first time slot and the relay node in second time slot appropriately, which can introduce cooperative diversity gain.

In dual-hop cooperative relaying LV PLC systems, the relay node can deal with the received signals in either AF or DF mode. In AF mode, the relay node amplifies the received signal which is affected by channel attenuation and noises, then retransmits it to the destination node, so that it's simple to implement but likely to cause error propagation. In DF mode, the relay node decodes and encodes the received signal, then retransmit the regenerated signal to the destination node. It's clearly noticed that the implementation of the relay node in DF mode is much more complicated than that in AF mode.

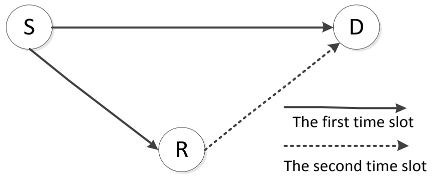

Fig. 3. Dual-hop relaying scheme

Assume that fully channel knowledge as well as perfect synchronization at the receiver and no channel state information at the transmitter. Fully channel knowledge at the receiver implies that the source-to-relay channel is perfectly known to the relay node, and the source-to-destination, relay-to-destination and source-to-relay channels are well known to the destination node.

We assume that the bandwidth of broadband LV PLC system is *B*. The channel frequency response between each pair of nodes is denoted as $H_{xy}(f,d)$ and the noise PSD between each pair of nodes is denoted as $N_{xy}(f)$ where the subscripts *x*, *y*, denote the pairs {S, R}, {S, D}, {R, D}.

A. Direct Transmission Mode (DT)

For DT scheme, the signal is transmitted from the source node to the destination directly, so the system capacity is

$$C_{DT}(d) = \int_B \log_2(1+\frac{|H_{sd}(f,d)|^2 P_s(f)}{N(f)})df \qquad (3)$$

Clearly, the system capacity in DT mode is a function of distance *d* and $P_s(f)$.

B. Amplify-and-Forward with Non-Cooperative Relaying Mode (AF NCR)

For the AF NCR relaying scheme, the source node sends the signal to the relay node in the first time slot. The signal received from the source node and amplifies the received signal according to its power constraint, then retransmits it to the destination node. The equivalent end-to-end signal noise ratio (SNR) is computed as [11]

$$r_{equ}^{AF\text{-NCR}}(f) = \frac{r_{sr}(f,d_{sr})r_{rd}(f,d_{rd})}{1+r_{sr}(f,d_{sr})+r_{rd}(f,d_{rd})} \qquad (4)$$

where

$$r_{xy}(f,d_{xy}) = \frac{P_x(f)|H_{xy}(f,d_{xy})|^2}{N_y(f)} \qquad (5)$$

Represents the SNR from node *x* to node *y* , *x*, *y* denote the pairs {S, R}, {S, D}, {R, D}.

So the system capacity of non-cooperative AF relaying system is computed as

$$C_{AF-NCR}(d) = \frac{1}{2}\int_B log_2(1+r_{equ}^{AF-NCR}(f))df \qquad (6)$$

where the factor 1/2 accounts for the fact that information is conveyed to the destination node over two time slots.

C. Cooperative AF Relaying Mode (AF CR)

For the cooperative AF relaying scheme, the source node sends the signal to the relay node in the first time slot. The relay node receives the signal from the source node and amplifies the received signal according to its power constraint, then retransmits it to the destination node. The destination node combines the signal received from the source node in the first time slot and from the relay node in the second time slot with maximum ratio combiner. The equivalent end-to-end SNR is expressed as

$$r_{equ}^{AF}(f) = r_{sd}(f,d_{sd}) + \frac{r_{sr}(f,d_{sr})r_{rd}(f,d_{rd})}{1+r_{sr}(f,d_{sr})+r_{rd}(f,d_{rd})} \qquad (7)$$

So the system capacity of cooperative AF relaying system is expressed as

$$C_{AF}(d) = \frac{1}{2}\int_B \log_2(1+r_{equ}^{AF}(f))df \qquad (8)$$

D. Decode-and-Forward with Non-Cooperative Relaying Mode (DF NCR)

For the DF NCR scheme, the source node sends the signal to the relay node in the first time slot, the relay node decode the received signal and retransmits it to the destination node. The maximum system capacity of DF NCR relaying system can be expressed as

$$C_{DF\text{-}NCR}(f)=\frac{1}{2}\int_B \min\left\{\log_2\left(1+\frac{|H_{sr}(f,d_{sr})|^2\ P_s(f)}{N_r(f)}\right),\right.\left.\log_2\left(1+\frac{|H_{rd}(f,d_{rd})|^2\ P_r(f)}{N_d(f)}\right)\right\}df \tag{9}$$

E. Cooperative DF Relaying Mode (DF CR)

For the cooperative DF relaying scheme, the source node sends the signal to the relay node and the destination node in the first time slot. The relay node decode the received signal from the source node and encode the signal, then retransmits it to the destination node. The destination node combines the signal received from the source node in the first time slot and from the relay node in the second time slot with maximum ratio combiner. The maximum system capacity of cooperative DF relaying system can be shown as

$$C_{DF}(f)=\frac{1}{2}\int_B \min\left\{\log_2\left(1+\frac{|H_{sr}(f,d_{sr})|^2\ P_s(f)}{N_r(f)}\right),\right.\left.\log_2\left(1+\frac{|H_{sd}(f,d_{sd})|^2\ P_s(f)}{N_d(f)}+\frac{|H_{rd}(f,d_{rd})|^2\ P_r(f)}{N_d(f)}\right)\right\}df \tag{10}$$

IV. EMC Regulations in LV PLV System

As we known, the system capacity is increasing with increasing transmit power. The EMC regulations of PLC systems limit the transmit power to a certain low value since the electromagnetic radiation produced by the PLC transmit power will interfere with other radio services which work on the same frequency band with PLC.

TABLE I: DIFFERENT EMC REGULATIONS IN DIFFERENT REGIONS

Enforced Region	EMC regulations	EMC regulated Power in PLC systems
The United States	FCC Part 15	-60dBmW/Hz
European Union	EN55022 Class B	-67dBmW/Hz
Germany	German Law NB30	-93dBmW/Hz

As shown in Table I, The EMC regulations in different regions have different threshold values of transmit PSD. Federal Communications Commission (FCC) Part 15 in the United States suggests PLC transmit Power Spectral Density (PSD) to be lower than -60dBmW/Hz, EN55022 Class B in European Union suggests to be lower than -67dBmW/Hz and German Law NB30 in Germany suggests to be lower than -93dBmW/Hz [9]. Like other communication systems, the system capacity is varying with transmit power. Therefore different regions can achieve different maximum LV PLC system capacities according to their local EMC regulations.

As depicted in Fig. 4, the system capacities decrease with S-D distance and transmit power. The PLC system has the highest maximum capacity in the United States and has the smallest maximum capacity in Germany. In the following numerical simulations, the three EMC regulations are all adopted in each cooperative relay-aided PLC system mode respectively.

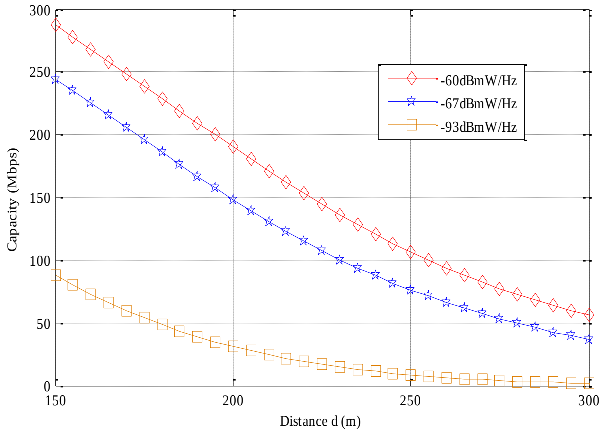

Fig. 4. The system maximum capacities in DT mode under EMC regulations.

V. Numerical Analysis

In this section, the performance of the dual-hop cooperative relaying systems over LV PLC channel in cooperative AF relaying mode (AF CR), cooperative DF relaying mode (DF CR) are compared with that in DT mode, non-cooperative AF relaying mode (AF NCR) and non-cooperative DF relaying mode (DF NCR) by numerical simulations. Finally, the effect of the relay node locations to system capacity is illustrated by simulations.

For the LV PLC systems, the total bandwidth for the simulation is set from 2 to 20.6368MHz, which is a typical range for broadband LV PLC network. Assuming an OFDM scheme is applied for simulations. We assume that the total bandwidth is divided to 512 subcarriers while $\Delta f=36.4\text{kHz}$. The subcarrier bandwidth is sufficiently small such that each subcarrier is considered to be frequency-flat, and the average frequency response in each subcarrier is considered as the subcarrier frequency response.

A. Comparison of System Capacity

In this subsection, we use an uniform relay setup, where the relay is located halfway between the source node and the destination node, i.e., relay location ratio $\alpha_r=d_{sr}/d_{sd}=1/2$. To facilitate the capacity gain analysis, we define

$$G_{capacity} = \frac{C_{relay-aided} - C_{DT}}{C_{DT}} \tag{11}$$

where $C_{relay-aided}$ and C_{DT} denote the system capacities of the transmission with and without the help of a relay node respectively.

Transmit PSD complying with FCC Part 15 in the United States: The transmit PSD of the source node and the relay node is chosen to be -60dBmW/Hz according to EMC regulation in FCC Part 15. For comparison purpose, the system capacities of Non-cooperative (NCR) modes are plotted as well. Fig. 5 and Fig. 6 show the system capacities in DT, AF NCR, AF CR, DF NCR and DF CR mode with S-D distance d when the transmit *PSD*=-60dBmW/Hz and capacity gains of relay-aided systems respectively.

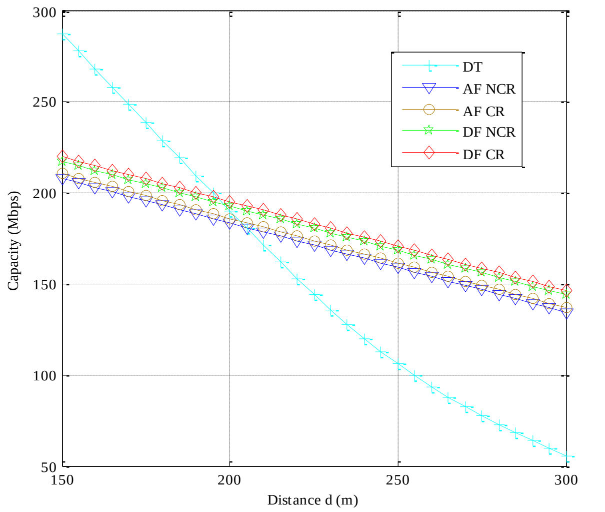

Fig. 5. The system capacities in DT, AF NCR, AF CR, DF NCR and DF CR mode when the transmit PSD=-60dBmW/Hz.

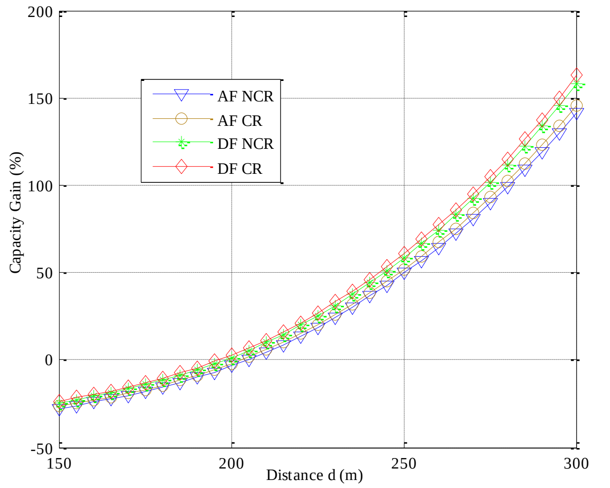

Fig. 6. The capacities gain in relay-aided modes compared with in DT mode when the transmit PSD=-60dBmW/Hz.

It's noted that when the S-R distance $d > 200$m, the relay-aided system capacities are all larger than capacity in DT mode. The system capacities in DF mode exceed the system capacities in AF mode. Furthermore, the CR scheme achieves greater capacity improvement than NCR scheme. Among all relay-aided systems, the system capacity in DF CR mode is the highest while in AF NCR mode is the smallest. The system capacity in DF CR mode is $5.75\% - 8.95\%$ higher than in AF NCR mode when S-D distance between 150m and 300m. The capacity gain increases with S-D distance d. The capacity gain in DF CR mode is *53%* at $d = 250$m and it increases with S-D distance d. At $d = 300$m, the capacity gain in DF CR mode is 162%.

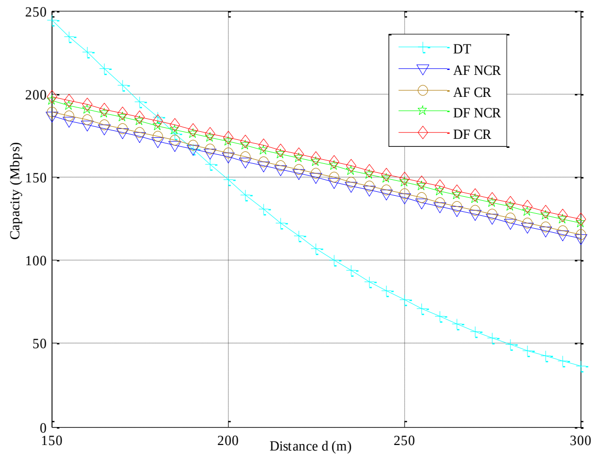

Fig. 7. The system capacities in DT, AF NCR, AF CR, DF NCR and DF CR mode when the transmit PSD=-67dBmW/Hz.

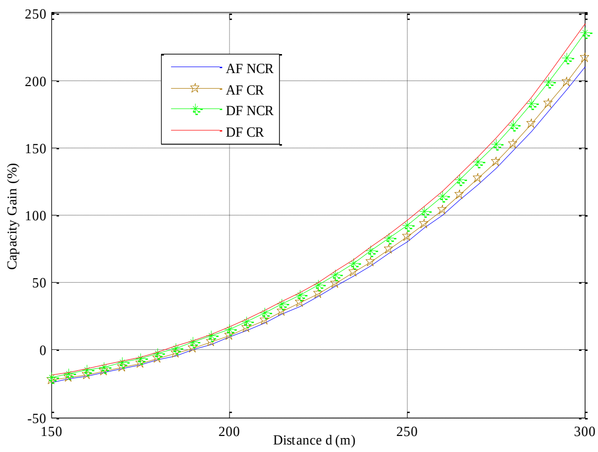

Fig. 8. The capacities gain in relay-aided modes compared with in DT mode when the transmit PSD=-67dBmW/Hz.

Transmit PSD complying with EN55022 Class B in the European Union: The transmit PSD of the source node and the relay node are chosen to be -67dBmW/Hz according to EMC regulation in EN55022 Class B. Fig. 7 and Fig. 8 show the system capacities in DT, AF NCR, AF CR, DF NCR and DF CR mode with S-D distance d when the transmit *PSD*=-67dBmW/Hz and capacity gains of relay-aided systems respectively.

From figures, we also notice that the relay-aided system capacities outperform the DT system when $d > 185$ m. System capacity in DF CR mode is $6.39\% - 10.42\%$ more than in AF NCR mode when S-D distance between 150m and 300m. The capacity gain in

DF CR mode is *85%* at d=250m. At d=300m, the capacity gain in DF CR mode is 242%.

Transmit PSD complying with German Law NB30 in the Germany: The transmit PSD of the source node and the relay node is chosen to be -93dBmW/Hz according to EMC regulation in German Law NB30. Fig. 9 and Fig. 10 show the system capacities in DT, AF NCR, AF CR, DF NCR and DF CR mode with S-D distance d when the transmit PSD=-93dBmW/Hz and capacity gains of relay-aided systems respectively.

The figures reveal that the relay-aided system capacities almost outperform the DT system in all ranging of distance d_{sd} from 150m to 300m. System capacity in DF CR mode is 11.25%-26.86% more than in AF NCR mode when S-D distance between 150m and 300m. The capacity gain in DF CR mode is 634% at d=250m.

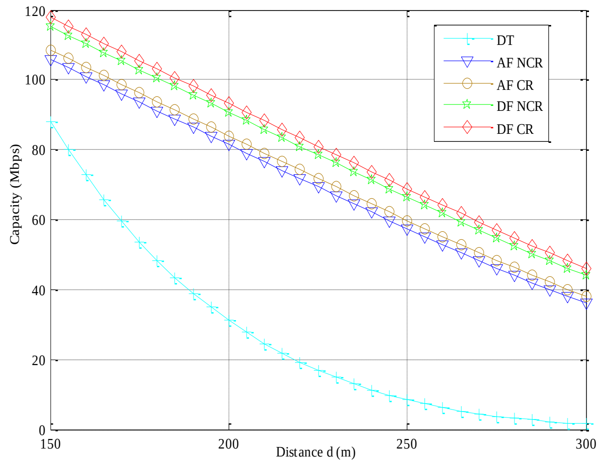

Fig. 9. The system capacities in DT, AF NCR, AF CR, DF NCR and DF CR mode when the transmit PSD=-93dBmW/Hz.

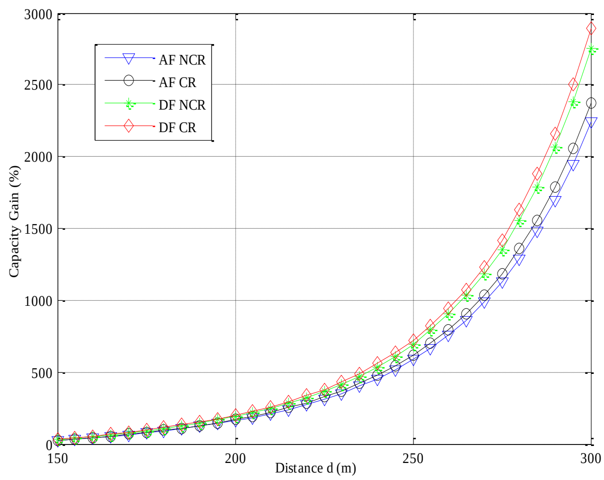

Fig. 10. The capacities gain in relay-aided modes compared with in DT mode when the transmit PSD=-93dBmW/Hz.

B. *Effect of Relay Locations to System Capacity*

To illustrate the effect of relay locations to system capacity, we move the relay node along with the line of the source node and the destination node and calculate the system capacities with different relay locations. We simulate in AF CR mode, S-D distance d=250m, the transmit PSD of the source node and the relay node is -60dBmW/Hz. Fig. 11 shows the system capacities vary greatly with the relay locations. It's clearly noted that the location of the relay node is a critical factor to system capacity and the best location is in the middle of the S-D link. Furthermore, in AF NCR LV PLC system with S-D distance d=250m, the relay-aided system capacity outperforms the DT mode whenever the relay location ratio between 0.24 and 0.76.

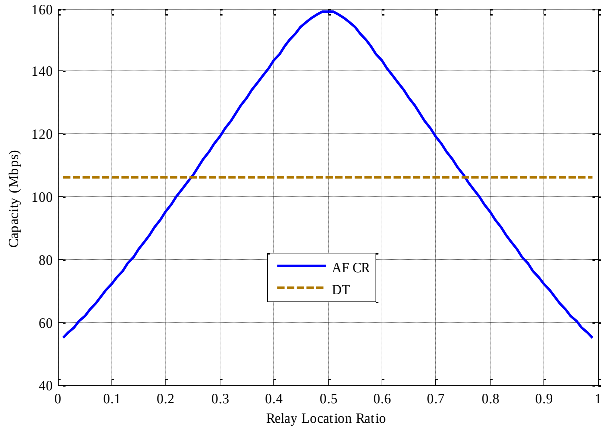

Fig. 11. The system capacities with the relay location ratio with S-D distance d=250m, transmit PSD is -60dBmW/Hz.

VI. CONCLUSIONS

In this paper, we have studied the system capacities of dual-hop relaying systems with non-cooperative and cooperative mode for LV broadband PLC networks. First, both AF and DF modes are introduced and the closed-form expressions of system capacities are derived. Secondly, the system capacities of relay-aided systems are simulated over the prevalent LV PLC channel complying with different EMC regulations in different regions respectively. The numerical results show that the relaying schemes are very beneficial in LV PLC networks when the S-R distance is more than a certain threshold. The lower transmit PSD the system is limited, the more prominent capacity gain the relay-aided systems obtain. Among the cooperative and non-cooperative relay modes, the DF CR system achieves the highest system capacity while the AF NCR system achieves the smallest. Finally, numerical results are presented to reveal the effect of relay locations to system capacities. The system capacities vary with the relay locations greatly so that it's of great importance to choose an appropriate position for the relay node. The best relay position is located in the middle of the line of S-D link in LV PLC channel.

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