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Decode and Forward Relay-Assisted Power-Line Communication

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Abstract

Capacity and coverage represent challenges for any kind of network, including electric ones. In view of data exchange over the existing infrastructure, many factors can directly influence the quality of the transmitted signal. With the arrival of Smart Grids new challenges arise to improve the current transmission conditions by including information technologies such as wireless communication and especially the use of relay stations. This has been the object of many researches seeking a better quality of service.

In this paper we will discuss the contribution of the integration of a relay station with a power-line communication (PLC). Discussion is about comparing the capacity of the relay-assisted PLC to the direct transmission capacity. Two relaying protocols are considered. In fact, comparison concerns the Decode and Forward (DF) and the Amplify and Forward (AF) protocols. The DF relay is using the Joint Modulation technique (DF-JM). Simulation, based on theoretical studies, aims to compare the capacity of the wired system (PLC) when considering a frequency selective channel, with a relay-assisted one (RA-PLC) where the time and power allocation play important role in capacity improvement. The simulation considers different cable length and relay transmit power. It also covers different position of the relay station.

Results have proved that the performance of the transmission through the relay station exceed direct transmission regardless the cable length. Concerning wireless communication, the DF protocol gives higher capacity when compared to the AF in the case of using equal resource allocation (time, power) and optimized values. This result shows the contribution of the DF-JM relaying protocol when added to a wired communication system in a smart grid environment, in conformity to the outcomes previously concluded in purely wireless systems.

Keywords: Power-Line Communication ; Relaying ; Decode and Forward ; Joint Modulation ; Amplify and Forward.

1. Introduction

The development and the evolution of the power grids infrastructure has stopped for hundreds of years, which made it technically an old system that may fail and not respond at any moment. In that time, the use of electricity and
its requirements had increased steadily, making this infrastructure unable to support them in terms of importance of flows and transmission quality, especially when it comes to the integration of intelligent networks. This integration has emerged the Smart Grid (SG) concept.

By definition, a smart grid is a modernized electric power grid infrastructure which aims to integrate larger amounts of distributed energy into the grid with improving efficiency and reliability through automated control tools and recent communication technologies.

1.1. Motivation

Modern society and economy are nowadays requiring a large scale of smart electric grids that offer reliable services and high quality power flow. Consequently, the existing electrical infrastructure became unable to satisfy the increasing communication needs. Therefore an integration of modern wired or wireless technologies appears necessary to improve the system efficiency.

For instance, including wireless technologies on power-line transmission is playing a major role in supporting data exchange in Smart Grid (SG). It has ensured greater degree of scalability and better quality of service in regarding to delay, throughput, error rate, etc. However, under the limitation caused by radio transmission and interference problems, advanced technologies should be deployed to respond to SG challenges. Repeaters and relays are taking part in the process.

1.2. Related works

Using the existing infrastructure, the communication over the electric power grid has no need to additional wiring, which make it an uncomplicated and cheap solution to set a network in any existing establishment. Therefore, improving PLC system has reviewed light with multiple works.

Taking advantage of the similarity between current standards for a broadband power-line communication (BPLC) and wireless standards at the physical layer using both the orthogonal frequency division multiplexing (OFDM), including wireless technologies in smart grids has improved and simplified data exchange between various components of the grid (generation, transmission, distribution, and consumer). Among wireless technologies, the use of the relay stations has proved its efficiency in the development of the smart grids through many years. They are included in each part of the grid, which encourages standardization works with referring to the system needs and communication requirements.

Recent works discussed embedded relays in power-line communication networks. In transmission over a frequency selective power-line channel assisted with a one way relay using the Amplify and Forward (AF) protocol in a frequency band ranging up to 30MHz, achieves higher capacity compared to the direct link transmission, where this relay is located at different positions. In view of the intensive research on relaying systems and techniques, this comparison can still give better results using a protocol that showed more efficiency compared to the Amplify and forward, because of its amplification criterion that promotes error proliferation during the data exchange.

Considering the bidirectional criterion of data exchange in SG, integration of two way communication network to convey information from and to consumers is a choice to improve in transmission delay and then response time towards consumer. A discussion compared several relaying protocols including Amplify and Forward and Decode and Forward in a broadband PLC system, for a frequency selective fading channel using one relay or more, in a simple and bidirectional sense. Decode and Forward (DF) appears to give more robust performance. That having been proved, a question arises whether this protocol will always confirm effectiveness when integrated in a wired medium with different transmit power and cabling characteristics, which will also influence the interference conditions and the error rate during data transmission.

To optimize the DF protocol potential in cooperative transmission, a recent study considered a two way wireless communication system using a Decode and Forward relay. The researcher investigated DF strategies and showed that Decode and Forward with Joint Modulation (JM) technique outperforms DF with Network Superposition Coding (NSC) in terms of total rate. This result gives ambitions for better relaying in a power-line environment for smart grids, especially when we talk about bidirectional communication.
1.3. Contribution

In this work, and in order to take advantage of these works previously done, we will adopt the wired system considered in\(^8\) using a relay station, with DF protocol this time. Even more, simple communication will be replaced with a bidirectional one. To do this and ensure better results, we will adopt the DF-JM protocol that has proved best performance in a wireless environment\(^9\), and study its influence and contribution when integrated in a wired system. The evaluation and comparison will include resource optimization (time allocation and transmit power) according to the corresponding protocol.

Therefore, we consider a dual hop relay aided power-line system. Transmitted signal is interfered with an additive white Gaussian noise. In section II, we present the transmission system model on which we will work. The evaluation is based on a signal attenuation model for a frequency selective relay channel. The interpretation of the overall capacity is based on comparison with other techniques described in section III. At first we study the system capacity for a direct transmission over a power-line. Results are then compared to the relay aided transmission capacities. Later in section IV, numerical simulations are presented to validate theoretical studies. To defend the chosen protocol, we are going to compare it to the Amplify and Forward (AF) protocol, with reference to relevant research studies.

2. System modeling

We consider a dual hop transmission network as described in Fig. 1. The system is composed of three nodes (source S1, source S2 and relay R). The communication between S1 and S2 takes place with two sorts of links: a direct connection via a power-line, and a relay aided connection where the intermediate node (the relay) receives the transmitted message from the source, treats the signal and sends it to the destination. Each node cannot receive and transmit messages at the same time.

The two-way information exchange ends in two time slots for both paths. For the cooperative transmission, during the first time slot S1 and S2 send their message (respectively W1 and W2) simultaneously to the relay node. The relay R applies Decode and Forward protocol to create a resulting signal broadcasted to sources all along the second time slot.

Considering Joint Modulation strategy for Decode and Forward relay\(^11\), after collecting sent messages from sources, the relay jointly decodes and then combines them into a new sequence (W1, W2) on which it applies a generation function to construct the second time slot’s output Yr=G(W1, W2).

3. Resources optimization and capacity analysis

Evaluation of transmission quality can be based on several factors. When talking about capacity, time and transmit power present an important resources that directly influence on the overall data rate. In this section we treat at first the transmit power optimization problem for a direct transmission. Found results will be compared to the capacity of a DF-JM assisted system when optimizing time allocation.

3.1. Direct transmission

To maximize the overall capacity in a frequency selective channel, the control of power allocation between subcarriers was always a subject of research. The principal used technique is the Water Filling algorithm. According to
that, the power allocation in an OFDM channel with N sub-channels \( (P_n) \) is the solution to the optimization problem given by\( ^{12} \):

\[
C_n = \max_{P_0,\ldots,P_N} \sum_{n=0}^{N-1} \log \left( 1 + \frac{P_n|h_n|^2}{N_0} \right)
\]

subject to:

\[
\sum_{n=0}^{N-1} P_n = P_{total}
\]

\[
P_n \geq 0
\]

Where \( P_n \) and \( h_n \) represent respectively the transmit power, channel response for each sub-carrier with \( P_{total} \) as a total power constraint. The Noise spectral density is designed with \( N_0 \).

Using the Lagrangian Method to solve (1), the optimum power allocation \( (P_n^*) \) is expressed with:

\[
P_n^* = \left( \frac{1}{\lambda} - \frac{N_0}{|h_n|^2} \right)^+ = \begin{cases} \frac{1}{\lambda} - \frac{N_0}{|h_n|^2} & \text{if } \left( \frac{1}{\lambda} - \frac{N_0}{|h_n|^2} \right) \geq 0 \\ 0 & \text{otherwise} \end{cases}
\]

Where \( \lambda \) is the Lagrange multiplier satisfying the power constraint in (1), and the \((x)^+\) expression means the maximum of \( x \) in zero \((\max(x, 0))\).

Thus, using previous findings\(^8\), system capacity for a simple direct link transmission \( (C_{DL}) \) can be defined with equation (3) subject to the total transmit power \( P \):

\[
C_{DL} = \max_{P(f) : \|P(f)\|_F \leq P} \int B \log \left( 1 + \frac{P(f)|h(D,f)|^2}{N(f)} \right)
\]

where \( P(f) \) represents the transmit power at a frequency \( f \), \( h(D,f) \) is the channel response over a distance \( D \), and \( N(f) \) as the background noise. Substituting the optimal power expression (2) in (3), the final capacity is given by:

\[
C_{DL} = \int B \log \left( 1 + \frac{|h(D,f)|^2}{\lambda N(f)} \right)
\]

where \( B \) is defined as the signal bandwidth and expressed by : \( B = \{ f : \frac{1}{\lambda} - \frac{N(f)}{|h(D,f)|^2} > 0 \} \).

3.2. Relay-assisted transmission

For the considered system model, the achievable data rate under a Joint Modulation relay \( (C_{JM}) \) is defined by a couple sum rates as follows\(^{10} \):

\[
C_{JM} = \{ (C_1, C_2) : C_1 \leq \min(C_1, C_2), C_2 \leq \min(C_2, C_1), C_1 + C_2 \leq C_r \}
\]

where we define \( L(x) = \log(1 + x) \)

and

\[
C_{1r} = tL \left( \frac{P_1|h_1|^2}{N_0} \right), \quad C_{2r} = tL \left( \frac{P_2|h_2|^2}{N_0} \right)
\]

\[
C_{r1} = (1-t)L \left( \frac{P_1|h_1|^2}{N_0} \right), \quad C_{r2} = (1-t)L \left( \frac{P_2|h_2|^2}{N_0} \right)
\]

\[
C_r = tL \left( \frac{P_1|h_1|^2}{N_0} + \frac{P_2|h_2|^2}{N_0} \right)
\]

Where \( t \) represents the transmit time duration, \( P_i \) is the transmit power at node \( i \), \( h_i \) is the channel response from \( i \) to the relay, and \( C_{ij} \) is the total capacity from \( i \) to \( j \) with \( i, j \in \{ 1(source1), 2(source2), r(relay)) \). In order to maximize the total data rate, the JM optimization plays on time factor. In fact, referring to (5) it’s obvious that both \( C_{r1} \) and \( C_{r2} \) are decreasing in \( t \). Therefore, we aim to maximize the total capacity under lower time constraint. To do this,
we assume that one of the links rate should be above a threshold value $C_{th}$. Considering the case of $C_1 \geq C_{th}$ the optimization problem is illustrated by:

$$\max_{t} \left\{ C_{r_2} + C_{r_1} \right\}$$

s.t.

$$C_{th} \leq C_{r_2} \leq C_{1r}, \ C_{r_1} \leq C_{2r}$$
$$C_{r_2} + C_{r_1} \leq C_r, t \in (0, 1)$$

(6)

Regarding to capacities defined in (5), and substituted in (6), the expression of the optimal time allocation ($t^*$) can be derived as the maximum of the following four entities:

$$T = \max\left\{ \frac{R_{r_1} + R_{r_2}}{R_r + R_{r_1} + R_{r_2}}, \frac{C_{th}}{R_{r_1} + R_{r_2}}, \frac{R_{r_1}}{R_{r_2} + R_{r_1}} \right\}$$

where

$$R_1 = \frac{C_{1r}}{t}, \ R_2 = \frac{C_{2r}}{t}$$
$$R_{r_1} = \frac{C_{r_1}}{1-t}, \ R_{r_2} = \frac{C_{r_2}}{1-t}$$
$$R_r = \frac{C_r}{t}$$

(7)

where $R_{i,j}$ is equal to the capacity ($C_{ij}$) from i to j with $i, j \in \{1(\text{source 1}), 2(\text{source 2}), r(\text{relay})\}$ without the time factor, with $\psi$ the set of transmit power satisfying: $\psi = \{(P_r, P_1, P_2, C_{th}) : P_r \geq \frac{2(C_{th} - 1)}{|h|^2}\}$. In summary, we can define the optimal time allocation ($t^*$) as:

$$t^* = T \ \text{when} \ t^* \leq 1 - \frac{C_{th}}{R_{r_2}}$$

(8)

Thus, for any $P_r, P_1, P_2, C_{th}$ in $\psi$, $t^* = T$, else the system would not support the predefined threshold capacity $C_{th}$. Otherwise, with a $C_{th} = 0$, the optimal time is always equal to $T$.

In conclusion, the optimal total rate of the DF-JM relay ($C_{JM}$) is given by:

$$C_{JM} = \min\left\{ \frac{R_{r_1} + R_{r_2}}{1 + \frac{R_{r_1} + R_{r_2}}{R_{r_1} + R_{r_2}}}, \frac{R_{r_1} + R_{r_2}}{1 + \frac{R_{r_1} + R_{r_2}}{R_{r_1}}}, \left(1 - \frac{C_{th}}{R_1}\right)\left(\frac{R_{r_1} + R_{r_2}}{R_1}\right), \frac{R_{r_1} + R_{r_2}}{1 + \frac{R_{r_1} + R_{r_2}}{R_2}} \right\}$$

(9)

4. Numerical results

Through this section, we study the variation of the total capacity for transmission over a direct link and a relay aided system based on simulations developed with MATLAB. Specifically we make a comparative between Amplify and Forward strategy and Decode and Forward with Joint Modulation in order to determine the best protocol that will improve the total system capacity.

Simulation Scenarios are illustrated in Fig. 2 describing different communication paths used in the system. In the case of direct transmission (wired system), we consider a simple one way data exchange through a frequency selective channel. To send message from source 1 to source 2, an optimization of the transmit power should be made to choose the adequate carrier. On the other hand, when the system is assisted with a relay station, two protocols are involved. In the case of the Amplify and Forward relay, before each sent message an optimization of the transmit power is to be made (at source 1, and at the relay) according to (2). One way communication is done in two time slots. Concerning the DF protocol, we are studying the case of a bidirectional communication, when it takes two time slots to exchange data between sources. Time optimization is made at the beginning of the scenario according to (8).
For a power-line link with length $D$, the channel response is defined by $|h(f)| = e^{-(\alpha_0 + \alpha_1 f)D}$, with an attenuation factor $k = 0.7$, $\alpha_0 = 9.33 \times 10^{-3}$ and $\alpha_1 = 5.1 \times 10^{-3}$ corresponding to German low-voltage (LV) power distribution networks. The colored background noise density is calculated as $10 \log_{10}(N(f)) = N_0 + N_1 e^{-f/f_1} (\text{dbm}/\text{Hz})$ with $f_1 = 3.6$, $N_0 = -125$ and $N_1 = 35$ with reference to. The frequency unit is chosen MHz for all numerical applications.

Considering a transmission over the signal frequency band 2-20 MHz with a total transmit power 12.5 dbm, the variation of the capacity towards cable length is drawn on Fig. 3. Numerical results results show that, although the relay assisted PLC using the AF protocol (RA-PLC AF) shows better capacity compared to the direct transmission for long distance, the Decode and Forward adopting the Joint Modulation technique shows its out performance with both equal (RA-PLC eJM-DF) and optimal (RA-PLC optJM-DF) resources allocation. This means that, in spite of the possibility of the signal control to get an interference-free transmission through the power-line, this support seems to be less profitable due to the noise and the attenuation exerted on the signal. For this reason, significant capacity gains are achieved with the cooperative transmission system.
For Fig. 4, we choose to vary the relay transmit power and maintain the same power for the sources equal to $-63 \text{ dbm/Hz}$ for both protocols to interpret the change in capacity. As expected, the best result is still given by the optimized DF (DF-JM with optimal resource allocation), while the capacity under equal resources (DF-JM with eq-res) is approaching in higher power region which can be explained with (8) where the time duration is halved. These results show that higher achievement is obtained without strictly controlling the power transmitted by the relay, although time control and the number of simultaneously sent messages are important to boost up the increasing performance of the cooperative transmission system.

In fact, compared to AF, interference and noise at the relay node has a different effect on DF. That’s why when $Pr$ increase DF gives always better performance. This can be explained by the fact that the relay does not propagate its own experienced interference and noise to the destination.

Relay position is also a factor that influences the system capacity.
Looking for cost-effectiveness and network efficiency, in order to guarantee larger coverage with minimal deployment of relay stations, it’s necessary to know the optimal location of the relay node for maximizing network capacity. In Fig. 5, we observe the achievable rates under different position of the relay node where $d_1$ is the distance between the relay and source 1. It’s obvious that DF-JM yields the best performance in comparison to AF. We can notice that AF with optimal resource allocation meets AF with equal resources when the relay is in the middle. While approaching to one of the sources, the optimal value gives the higher capacity.

5. Conclusion

We aimed through this paper to maximize the capacity of the wired transmission system, over a power-line. To provide a better configuration of the system we introduced a relay station that serves as reinforcement for the signal. To study such a system, we referred to earlier work to assess the contribution of Decode and Forward protocol used by the relay. As the Joint Modulation strategy has provided better results, we chose to compare it to the direct transmission first and then to the Amplify and Forward protocol.

To do this, and in order to recover a maximum total capacity, we studied resource optimization problems in power and time allocation, and its effect on the change in capacitance. Simulation results showed a significant gain of the DF-JM protocol under optimal resources allocation with respect to other transmissions. This has been proved for different powers and position of the relay and also for various cable lengths. Even if case of equal resources, direct transmission and RA-AF showed a lower contribution.

This is mainly due to the bidirectional criterion introduced in our system that focuses on the time factor (delay), in view of predefined communication type between different components of Smart Grid networks. In addition, because of its amplification and error propagation, the AF protocol remains not recommended as first choice in such systems. However, the development of the DF protocol (in terms of data processing time at the relay station) can further improve transmission capacity and quality.

These results can bring efficiency in other power-line configuration, and further improve routing and networking performance for superior layers. To approach the real model and values, other simulations, instead of MATLAB, will be achieved through network simulator (NS3) to validate the theoretical model.

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