Relaying Technologies for Smart Grid Communications

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Abstract

Wireless technologies can support a broad range of smart grid applications including advanced metering infrastructure and demand response. However, there are many formidable challenges when wireless technologies are applied to the smart gird, such as the trade-offs between wireless coverage and capacity, the high reliability requirement for communication, and limited spectral resources. Relaying has emerged as one of the most promising candidate solutions for addressing these issues. In this article, an introduction to various relaying strategies is presented, together with a discussion of how to improve spectral efficiency and coverage in relay-based information and communications technology infrastructure for smart grid applications. Special attention is paid to the use of unidirectional relaying, collaborative beamforming, and bidirectional relaying strategies.

Introduction

There is a widely recognized need to upgrade existing electricity grids in order to improve power delivery, reduce operating costs, and support renewable energy sources. Due to the dependence of these goals on data acquisition and control, such smart grids must combine existing electricity grids with advanced information and communications technology (ICT) infrastructure. A mature smart grid will consist of a number of applications, such as supervisory control and data acquisition (SCADA), advanced metering infrastructure (AMI), and demand response (DR). As different applications require distinct degrees of coverage, capacity, reliability, security, and latency, the implementation of ICT infrastructure for smart grid networks raises many challenging design issues [1].

Most smart grid applications (e.g., SCADA and AMI) should exhibit high reliability, large coverage, and high security, while requiring different scales of latency and data rates (e.g., 0.1~1 s latency and 100 kb/s data rate for SCADA, and 10~20 s latency and 1 Mb/s data rate for AMI). Considering neighborhood area networks (NANs), both wireline and wireless technologies can be used to meet these requirements. In the former case, power line communications (PLC) is a natural solution [1]. Using PLC, relatively small equipment investment is needed because it uses existing power lines as the data transmission medium. Nevertheless, there are a number of challenges with PLC (e.g., low capacity).

In the latter case, either ZigBee or Wi-Fi can be employed to enable AMI and DR applications due to their good capacity and low transmit power [2, 3]. However, because of their low transmit power levels, both technologies have limited coverage. A wireless mesh network that consists of various nodes (e.g., WiFi and ZigBee) organized in a mesh topology can enhance the coverage [4–7]. In addition, wireless mesh networks are inherently more reliable as they can take advantage of self-forming and self-healing network concepts.

Wireless mesh architectures are usually implemented at the network layer or data link layer. Relevant research focuses on protocol design for transferring data between network entities [5–7]. The performance of a wireless mesh network depends on the quality, reliability, and efficiency of communications between different nodes in the network. Taking advantage of spatial diversity, relaying technologies can improve the performance of wireless links between neighboring nodes to meet the communication quality requirements of a wireless mesh network. However, conventional relaying technologies such as amplify-and-forward (AF) and decode-and-forward (DF) enhance the capacity at the expense of consuming resources such as radio frequency (RF) spectrum. Inefficient use of these resources could lead to low spectral efficiency. Thus, it is critical to study advanced relaying technologies to improve the spectral efficiency while retaining the advantages of relaying transmission.

In the remainder of this article, we first ana-

lyze the challenges of wireless technologies for the smart grid, and then introduce conventional relaying transmission strategies. Some advanced relaying strategies are then discussed. The aim of this study is to identify relaying strategies that can achieve greater spectral efficiency, extended transmission range, and improved reliability.

CHALLENGES OF ICT FOR SMART GRID

The smart grid ICT infrastructure should allow utilities to interact with their electrical devices as well as with the customers on a near-real-time basis. However, for any wireless technology, there are several challenges that still need to be addressed before their deployment on the smart grid. These challenges are described in the following subsections.

### COVERAGE AND CAPACITY TRADE-OFF

Some smart grid applications (e.g., SCADA and AMI) require the access network to cover a large area. Unfortunately, since the interference level increases as the number of nodes increases, the coverage of a wireless network has an inverse relationship with the channel capacity; therefore, there is a trade-off between coverage and capacity in conventional direct transmission systems.

One potential solution is to use relaying technologies, whereby one long wireless link is broken into two or more shorter lower-power links. Due to the inherent broadcast nature of the communications from the source, it may be possible for one or more nodes receiving strong signals from the source to forward them to the destination. Therefore, relaying transmission is an important technique to widen the coverage and enhance the capacity [8].

RELIABILITY

The reliability of a network can be defined in terms of its robustness, survivability, and sufficiency of its connectivity to support a prescribed level of performance. Most smart grid applications (e.g., AMI) require reliable communications paths from the customers back to the high-speed core network. However, radio propagation in wireless communications is affected by several factors, such as multipath fading, which may result in a temporary failure of the communication due to a severe drop in the received signal-to-noise ratio (SNR). Furthermore, wireless networks may suffer disruptions caused by adverse weather conditions (e.g., thunderstorms) that could attenuate the transmission ability of the wireless network.

Using relaying technologies, the transmit signal can be passed through both the direct communication channel and the relay channel(s). With the aid of a receiver combining strategy, the multipath fading effects can be averaged or even removed. Under adverse weather conditions, a direct transmission link may be blocked. It is feasible to build alternate links using the rest of the nodes, thus offering capabilities of self-forming and self-healing to the ICT infrastructure.
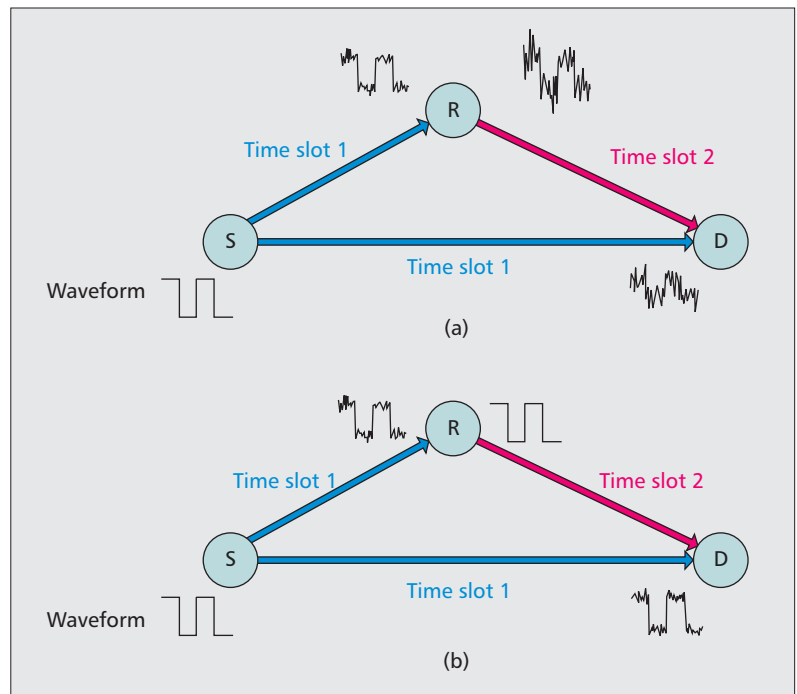
Figure 1. *Demonstration of conventional relaying protocols: a) amplify-and-forward (AF); b) decode-and-forward (DF).*

SPECTRUM ISSUES

RF spectrum is the lifeblood of wireless communication systems. However, current ICT for the smart grid has access to limited numbers of frequencies, which are primarily designated for SCADA and AMI. Using current transmission techniques, it is very challenging to support additional demands from certain new smart grid applications, such as video surveillance. The efficient use of RF spectrum is therefore a critical issue that needs to be addressed before the deployment of extensive wireless networking in the smart grid.

The spectral utilization efficiency is often measured by spectral efficiency, which is defined as the number of bits that can be communicated over a given bandwidth within a unit of time (in bits per second per Hertz).

Due to the contributions of relay channels, which can boost the signal strength at the destination, relaying technologies can achieve higher spectral efficiency than direct transmission.

CONVENTIONAL RELAYING STRATEGIES

Based on the above discussion, there is a common need for applying relaying technologies in wireless networks. We consider such a relay-based wireless system, where one or more relays working in the half-duplex mode are used to retransmit the signals to the destination (D). In this relay-based system, the data communication can be divided into two time slots. This is required due to the half-duplex constraint, which means that the relays are unable to receive and transmit data simultaneously. In the first time slot, the source (S) broadcasts its information to both D and one or more relays. In the second time slot, the relays forward the received data to

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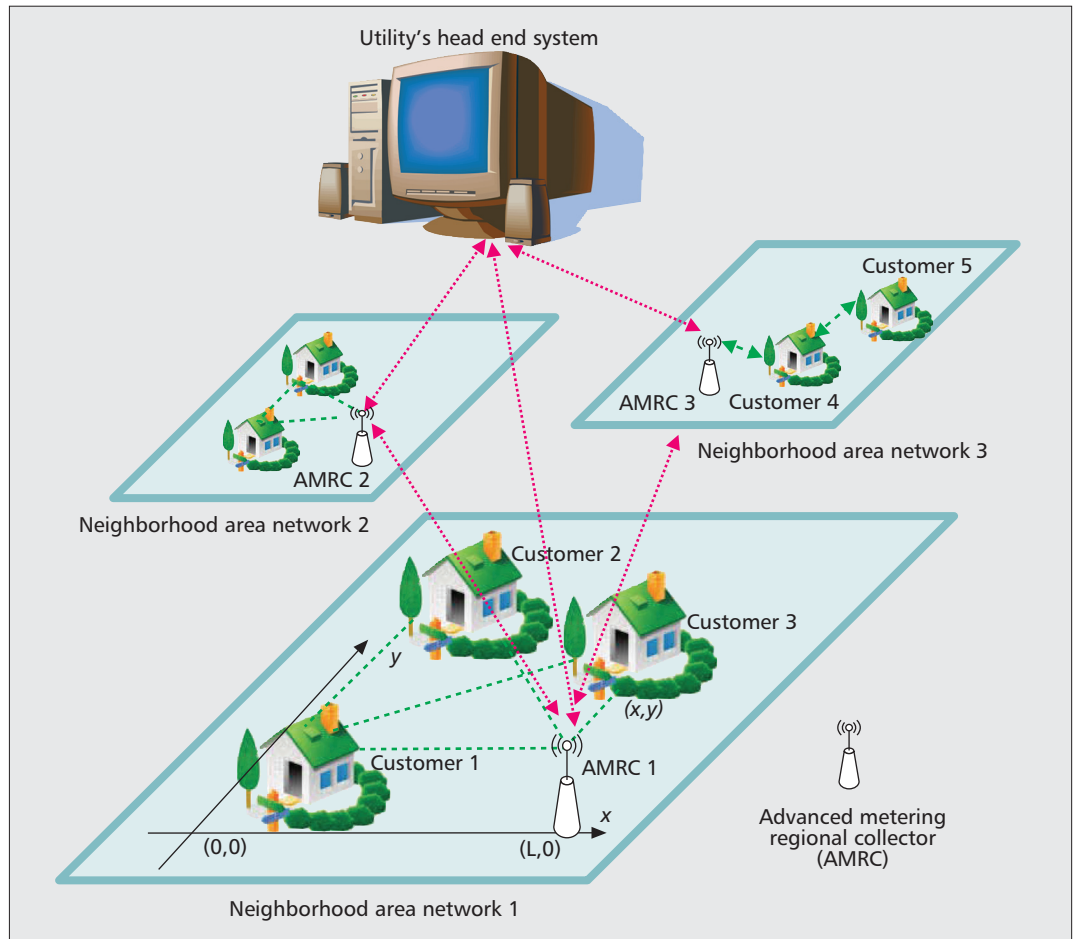
Figure 2. *An example of relaying technology implementation in the smart grid: relaying technology-based advanced metering infrastructure.*

D. By using relays, D could achieve much higher reliability in decoding the information from S by taking advantage of spatial diversity.

The main challenge in the relay-based system is how to use the relays efficiently, which requires study of how to use the relay(s) and also how many relays are needed. When we consider a single-relay system, the relaying protocol at the relay could significantly affect the system performance. Here, we present a brief overview of conventional relaying protocols (i.e., AF and DF). As illustrated in Fig. 1a, after the first time slot, one relay receives a noisy version of the transmitted signal from the source. The AF relaying protocol allows the relay to amplify and retransmit these noisy data to D.

Another simple relaying protocol is DF. As shown in Fig. 1b, the DF protocol allows the relay to decode the received signals from S and then re-encode and forward them to D. The performance of DF heavily depends on whether the relay can successfully decode the transmitted signals. If the relay fails to decode the signal correctly, it may be able to detect this through a cyclic redundancy check and not transmit the data. If the errors are not detected, they will be propagated to the destination and lead to even worse performance than for direct transmission. In either case, the relay is unable to improve detection performance at D.

On the other hand, if the signal is correctly decoded at the relay, the destination will receive a stronger signal and thus obtain improved performance.

CASE STUDIES FOR IMPROVING SPECTRAL EFFICIENCY OF RELAYING TRANSMISSION

It is noteworthy that the RF spectrum in the smart grid is a very valuable resource, as noted in the discussion earlier. Unfortunately, conventional relaying technologies (i.e., AF and DF) boost the signals at the destination at the expense of consuming extra resources (e.g., the time and spectrum allocated to the relay). Inefficient use of these resources leads to low spectral efficiency. The spectral efficiency loss in a multiple-relay system (e.g., a wireless mesh network) could be even worse if either multiple time slots or frequency bands are exclusively allocated to different relays. In order to improve the spectral efficiency while retaining the advantages of relaying transmission, it is necessary to study advanced relaying technologies. In the following subsections, we present two case studies that investigate two potential strategies: a two-relay system using beamforming concepts and a bidirectional relaying strategy for a two-way information exchange system.
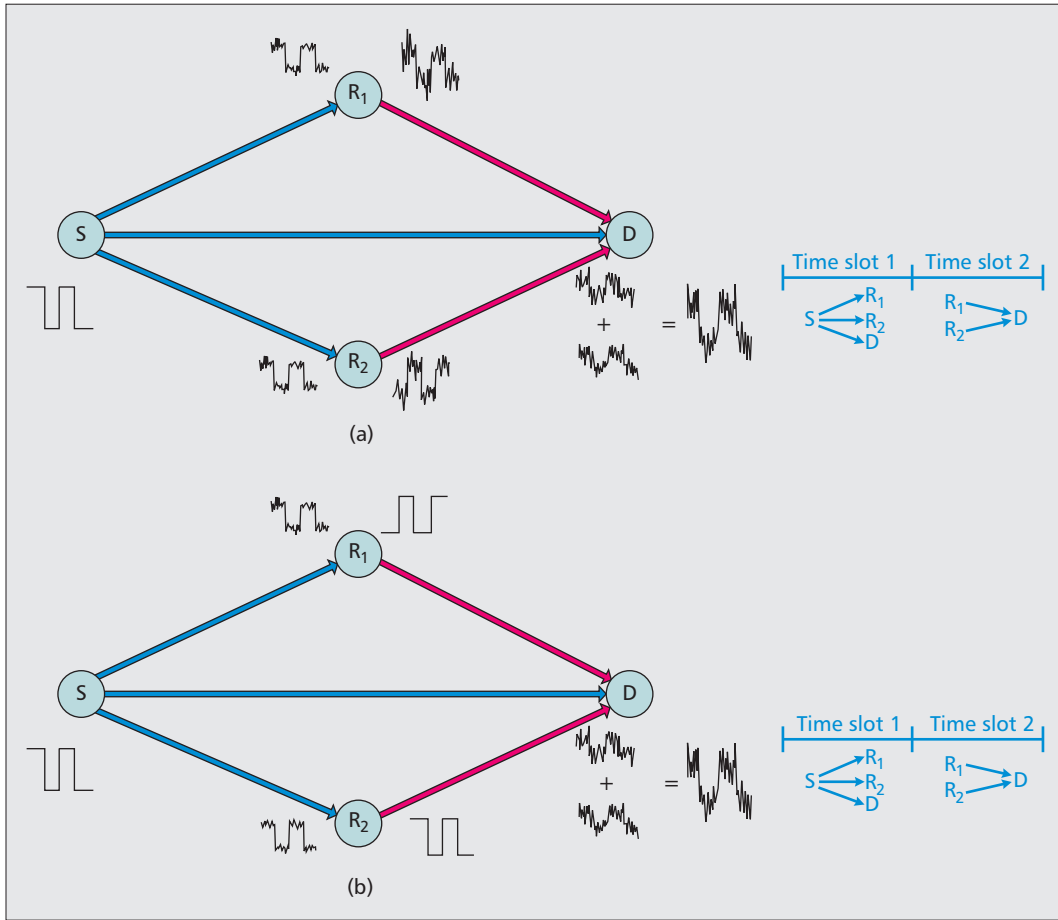
Figure 3. *Relaying protocols combined with 2-relay beamforming: a) unidirectional AF relaying protocol plus beamforming, and b) unidirectional DF relaying protocol plus beamforming.*

THE OVERALL SETTING

Considering AMI in the smart grid, the aim is to upload energy consumption data to the utility for DR applications. An example of a wireless network for implementing AMI is shown in Fig. 2. There are two scenarios in which relaying technologies can be used. In a NAN, customers 2 and 3 could act as relays that help customer 1 to transmit data to the advanced metering regional collector (AMRC). Furthermore, AMRCs can help each other to transmit data to the utility's head-end system (UHES). In the following, we discuss the implementation of relaying technologies in NANs.

Suppose that a NAN is implemented using wireless technology based on the ZigBee standard, and the channel center frequency is chosen to be $2405 + 5(k – 11)$ MHz, where the channel index k is a random integer in the range $k \in [11, 26]$. The bandwidth is assumed to be 2 MHz, and the channels between the relay and the end nodes are assumed to suffer frequency-flat Rayleigh fading. Considering the path loss, we adopt the International Telecommunication Union (ITU) indoor propagation model [10], in which the distance power loss coefficient is set to be 28 dB/decade. The transmit power is set to be 0 dBm, and the antenna gain is 2.5 dB. Additive white Gaussian noise (AWGN) is added to the communication channels with the power level of –110 dBm. Without significant loss of generality, all customers are assumed to be located on the x–y plane. Customer 1 is located at the origin $(0,0)$, and the AMRC is at the coordinates $(L, 0)$. The coordinates of the relay (either customer 2 or 3) are denoted by (x, y), where x and y are uniformly distributed values with ranges $x \in [0, L]$ and $y \in [–L/2, L2]$. To emulate the interference from other unlicensed spectrum users (e.g., WiFi or ZigBee), we assume that 1~3 users (with 3 dBm transmit power) are using the same frequency band, with random locations in the ranges $x \in [0, L]$ and $y \in [–L/2, L/2]$.

CASE STUDY 1: UNIDIRECTIONAL TWO-RELAY SYSTEM WITH COLLABORATIVE BEAMFORMING

Suppose that one smart meter of customer 1 (source) is uploading the data to the AMRC (destination) while two neighboring customers (relays) could assist the data transmission procedure. Using conventional relaying strategies, two relays forward certain versions of the received signals to the destination, as shown in Fig. 3a for AF and Fig. 3b for DF. No matter which relaying protocol is used, AF or DF, the two-relay system faces a challenge: Because of different channel phases at the two relays, the correlation properties of the received signals at the destination will be distorted. This means

a superposition of the signals at the destination will not necessarily strengthen the intended signals.

Collaborative beamforming [11] can be introduced to adaptively adjust the transmit signal phases and amplitudes at the two relays. For example, as shown in Fig. 3, the signal phase at relay 2 is adjusted. Taking advantage of collaborative beamforming, the received signals at the destination can be constructively added at the destination to improve SNR. To enable collaborative beamforming, the relays are assumed to be synchronized by the use of reference signals from a positioning system such as the global positioning system (GPS). In addition, we assume that the relays are sufficiently separated so that any mutual coupling effects among their antennas are negligible.

The spectral efficiencies of different relaying strategies are compared in Figs. 4a and 4b, where the x-axis denotes the distance between two end nodes and the y-axis denotes the system spectral efficiency. As shown in Fig. 4a, when direct transmission is available, relaying strategies yield spectral efficiency (also coverage) gain over direct transmission for any transmission distance. Beamforming in the unidirectional two-relay AF system results in marginal improvement compared to the single-relay AF strategy, while adding an extra relay node also increases system complexity. Meanwhile, the performance of the two-relay DF system with collaborative beamforming is similar to the single-relay DF strategy. This is because the overall information rate of the system is, in fact, limited by the channel conditions between the source and the two relays in the first time slot. One poorly conditioned channel from the source to one of the relays will eventually impair the overall spectral efficiency of the two-relay DF strategy. In Fig. 4b, we can see that if direct transmission is blocked, relaying technologies can still achieve satisfactory spectral efficiency.

The empirical cumulative distribution function (CDF) of spectral efficiency is shown in Figs. 4c and 4d, where the x-axis denotes the
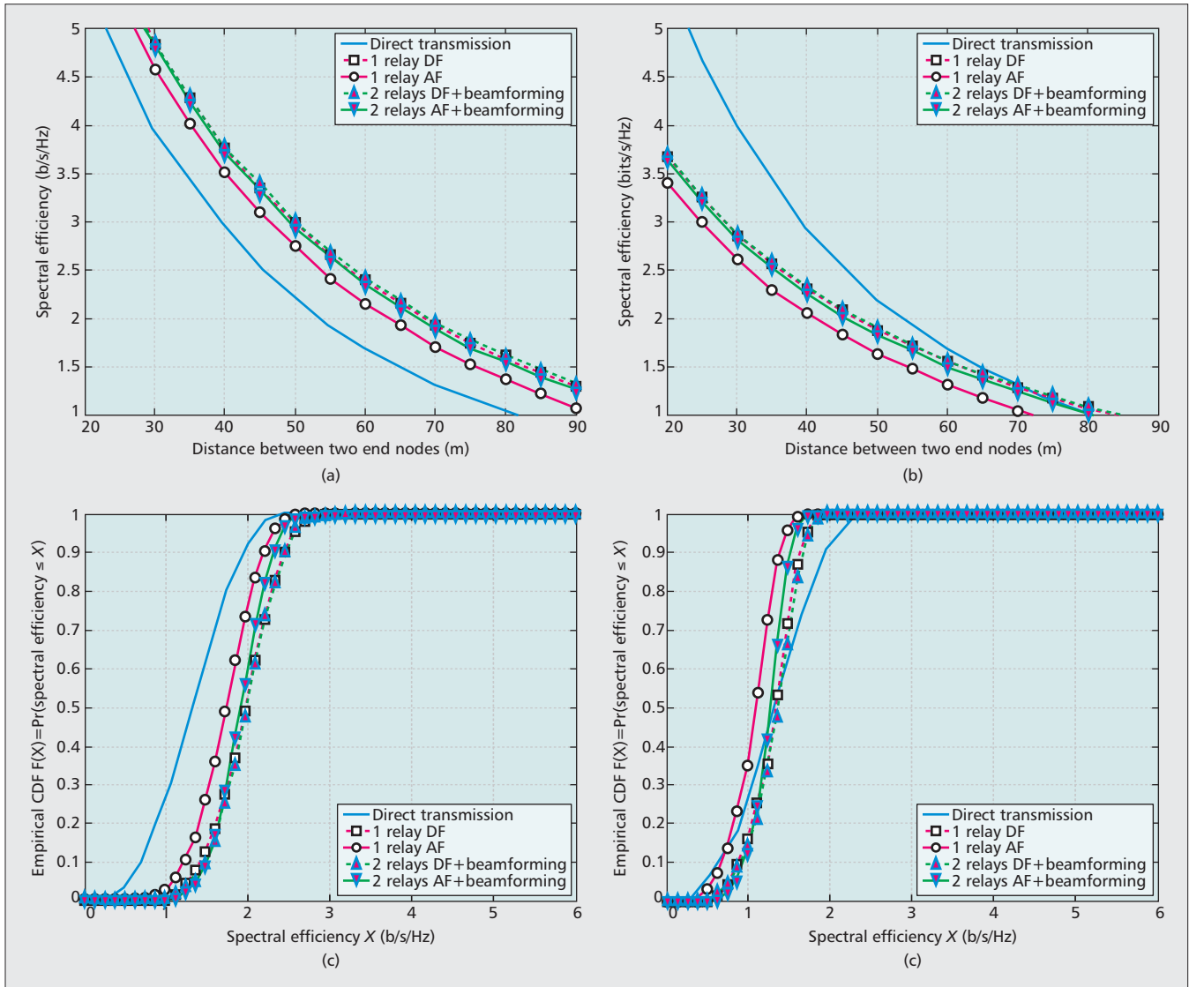
Figure 4. *Comparisons of relaying technologies with direct transmission: a) spectral efficiency when direct transmission is available; b) spectral efficiency when direct transmission is blocked; c) empirical spectral efficiency cumulative distribution function when direct transmission is available; d) empirical spectral efficiency cumulative distribution function when direct transmission is blocked.*

spectral efficiency X and the *y*-axis denotes the empirical CDF F(X). The spectral efficiency CDF F(X) is defined as the percentage of systems having a spectral efficiency less than or equal to X. The simulation results are based on an assumption that the distance between the two end nodes is 70 m. The CDF shows results for 10,000 different channel conditions for a given distance between the two end nodes. It should be emphasized that the steeper the curve, the more robust the system can be. In addition, shifting the curve to the right implies that it can obtain higher spectral efficiency. In Figs. 4c and 4d, we can see that all relaying strategies are more reliable than direct transmission.

Case Study 2: Bidirectional Relaying for Information-Exchange System

DR applications in the smart grid require high-data-rate two-way communications between the customers and the UHES. Using conventional unidirectional relaying strategies in NAN, four time slots are needed to accomplish the information exchange process, leading to low spectral efficiency.

As shown in Fig. 5, the bidirectional relaying strategy requires only two time slots to complete an information exchange process. In the first time slot, two end nodes (e.g., customer 5 and AMRC 3 in Fig. 2) send their information to the relay (e.g., customer 4) using the same frequency band, leading to a superposition of the received signals at the relay. Note that because we assume that all nodes are working in the half-duplex mode, two end nodes cannot decode the signals in the first time slot. Using the AF relaying protocol, the relay directly forwards its received signals to both end nodes. Because these two end nodes have their own copies of transmitted signals, they can subtract their own signals and obtain the information transmitted from the other node. We note that the channel state information between the relay and two end nodes can be estimated by using a channel estimation scheme, such as pilot symbol insertion or training bits [12, 13]. In this way, a higher spectral efficiency can be achieved, since the information at the two nodes is exchanged using fewer time slots.

If the bidirectional relaying strategy is applied together with the DF relaying protocol, the relay needs to decode the superposed signals. Optimal performance can be achieved using a maximum likelihood (ML) detection algorithm. Using ML, the detection error can be minimized but at the expense of high complexity. With lower computational cost, other approaches can obtain near ML performance. One approach is the so-called vertical Bell Labs layered space time (V-BLAST) detection algorithm [14]. Using V-BLAST, we first detect the signal from one node by treating the signal from another node as interference. We then subtract the detected signal vector from the received signal vector, and perform detection on the resulting signal vector. The advantage of the V-BLAST algorithm is that its computational complexity is low and fixed for the whole range of SNRs. Therefore, we consider the V-
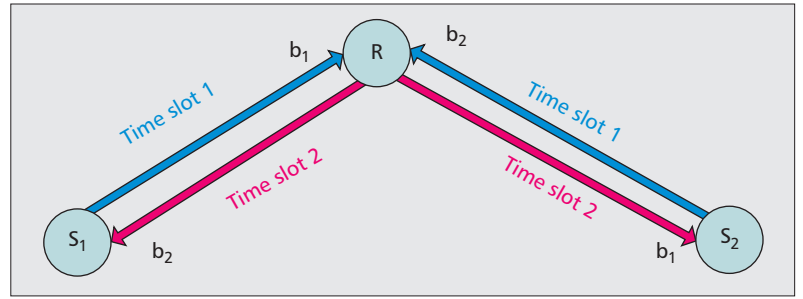
Figure 5. *A bidirectional relaying strategy that uses only two time slots when two end nodes exchange information.*

BLAST detection algorithm at the relay for the bidirectional DF relaying system.

It can be seen from Figs. 6a and 6b that despite the blocked direct transmission, the bidirectional relay strategies are always superior to direct transmission when the transmission distance is relatively long. This phenomenon arises from the facts that bidirectional relay strategies exchange information using fewer time slots than unidirectional relay strategies do, and that the bidirectional relay strategies do not use the direct link for transmitting information as the two end nodes are working in the half-duplex mode. Bidirectional DF is inferior to direct transmission when the transmission distance *L* is less than 35 m. This is because, when using V-BLAST, we treat the signal from another node as interference (it becomes stronger as the transmission distance becomes shorter), thereby decreasing the information rate of the whole system. Furthermore, we can see from Figs. 6c and 6d that even though the bidirectional relay strategies are not as reliable as the conventional relaying strategies, they can achieve higher spectral efficiency regardless of the availability of a direct transmission link.

Conclusions

In this article, we have discussed the challenges of wireless communication technologies when applied to the smart grid. In order to improve the coverage, spectral efficiency, and reliability of smart grid communications, we have investigated several potential relaying strategies (e.g., collaborative beamforming for multiple-relay systems and bidirectional relaying for information exchange systems). It has been shown that all relaying strategies can improve the reliability of smart grid communications thanks to spatial diversity. For DR applications, which require two-way information flow, the spectral efficiency and coverage of smart grid communications can be improved by using bidirectional relaying strategies. For SCADA applications where the data flow is mostly in one direction, two-relay systems can only achieve marginal improvement over a single-relay system at the expense of increased implementation complexity.

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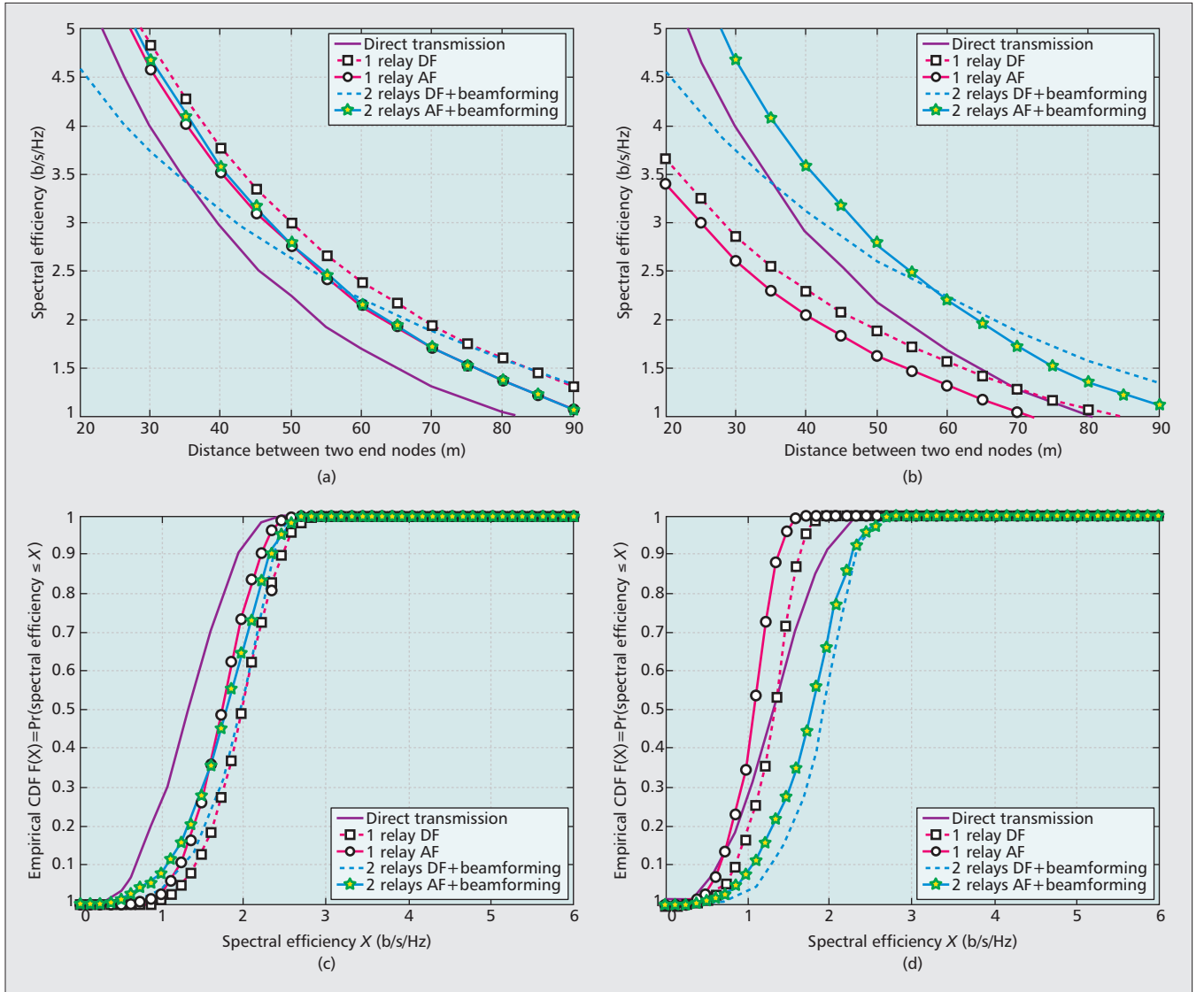
Figure 6. *Comparisons of relaying technologies with direct transmission: a) spectral efficiency when direct transmission is available; b) spectral efficiency when direct transmission is blocked; c) empirical spectral efficiency cumulative distribution function when direct transmission is available, d) empirical spectral efficiency cumulative distribution function when direct transmission is blocked.*

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