

Cooperative Wireless Transmission for Smart Metering

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Abstract—In order to optimize the power consumption and improve the energy efficiency, the smart grid (SG) provides reliable, efficient and secured electrical power generation and distribution. Smart grid aims to manage and control the consumer demand and provide the needed power. Thus, in smart grid architecture, the information about power supply must be known, in advance, by the operator. This information exchange is generally ensured through wireless communications. In the communication infrastructure, there is no place for transmission errors and high reliability is required. Also, a beforehand estimation of the next minutes consumption is desirable, to prepare the production, especially in the presence of distributed energy resources. In this paper, a Cooperative Wireless Transmission of Smart Metering called (CWT) is proposed to improve the transmission quality by reducing transmission errors and time delays. The objective is to gather the total of power consumption demand from every consumer and convey it simultaneously through a DAP (Data Aggregation Point) to the control center. Simulation results shows that CWT scheme outperforms the time division multiple access (TDMA) in terms of Cooperative Symbol Error Rate (CSER) and Power Metering Delay (PMD).

Index Terms—Smart Grid, Wireless Communication, Simultaneous Transmission, Power Supply

I. INTRODUCTION

In the traditional electrical grid, the majority of the produced electricity is based on fossil fuels, which is a manageable resource. Thus, the dispatching service can estimate the power demand 24 hours ahead, so the production can meet the need. However, due to the great demand growth observed these last years and the negative impact of fossil fuels on the environment, the integration of renewable energy (RE) becomes vital. Owing to the random nature of RE, it is necessary to have a clear idea on the power consumption in advance and faster than what it is done in the traditional electrical grid to be able to forecast the demand. To satisfy the time constraints, a new adequate architecture for the electrical grid is required. Smart grid (SG) is the term that designates the future electrical power grid using information technology to optimize the production, distribution and consumption and to reach the load-balancing. One of the most important techniques in SG is short term

load forecasting (STLF) [1]. It consists of estimating the consumption 24-h-ahead to prepare the production. However, since the RE is uncontrollable, we need a more frequent forecasting, we propose the very short-term load forecasting (VSTLF). The ability to forecast the load requirements is a powerful tool for the management of power systems. Thus, to reach a good quality of STLF, a simultaneous transmission is required. The communication technologies in SG could be either wired or wireless. Wireless communications such as cellular networks and wireless mesh networks can be used to connect the consumer to the operator [2]. It can offer a significant improvement for the smart grid network by providing: less-maintenance, low cost, low installation overhead and easy fault detection compared to the wired technologies. Nevertheless, wireless communications are subject to various radio propagation issues that can greatly affect the power supply information exchange. In [3] wireless network for real time and control power using Wireless Sensor Network (WSN) is designed for minimizing the cost and data latency. A new wireless architecture network is proposed in [4] for monitoring and distribution of electricity power. The proposed system aims to provide and save a large amount of power for the population of India. A cooperative wireless transmission scheme called Cooperative Dissemination of Power Price and Supply (CDPS) for smart grid is also proposed in [5]. CDPS scheme is a mechanism that aims to improve the operator's profit and reduce the amount of the wasted renewable power, by reducing transmission errors and giving access to all consumers to the power price and the power supply information.

In this paper, a cooperative wireless transmission of smart metering called (CWT) is proposed for a neighborhood smart grid, to allow a faster decision making process even if the number of users increases. The aim is to estimate the power consumption of a building, so the production can be prepared. A new pre-coding method based on zero-forcing at the transmitter side is proposed, in order to obtain the sum of the consumed power at the reception. Our main contribution is that multiple users can transmit the information about the total of the needed energy for their appliances simultaneously, permitting the prediction of the demand supply. To evaluate

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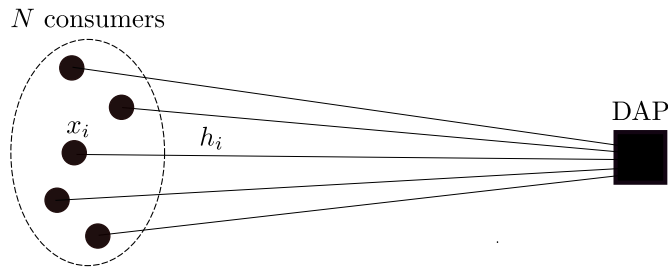


Fig. 1: The communication architecture for the smart building

our model, an analysis of the theoretical performance is given. Furthermore, a comparison between TDMA and CWT in terms of Cooperative Symbol Error Rate (CSER) and Power Metering Delay (PMD) is proposed.

The rest of this paper is organized as follows. In Section II, we present the system model of our work. We explain in details our simultaneous wireless communication approach for Neighborhood Area Network (NAN) in Section III. Simulation results are presented in Section IV and discussed. A conclusion of this paper is in Section V.

II. SYSTEM MODEL

We consider a smart neighbor with N consumer. Each house contains smart appliances, and these appliances are connected to one smart meter (SM) that gathers the information about the needed power in all the house. The SM sends a request to the Data aggregation Point (DAP) via wireless communication link as shown in Fig.1. The DAP transfers this request to the control center (CC), so as to satisfy the power demand at a time T . The CC will also be in charge of forecasting the power supply in the next time $T + 1$.

The transmitted signal from the consumer to the DAP crosses a multi-path channel. As a result, the characteristics of the channel change over the time and this causes time delays for the transmission, which is intolerable in smart grid applications. Because time delays differ significantly from a consumer to another, we chose the Nakagami fading as an appropriate model for our system's channel. For every link, the received signal is then given by,

$$y_i = x_i h_i + n, \quad (1)$$

where n is a complex zero-mean white Gaussian random process with power spectral density $No/2$. The fading coefficients h_i are zero-mean complex Gaussian random variables.

III. COOPERATIVE WIRELESS TRANSMISSION

In [5], a cooperative wireless transmission of dynamic Power Price and Supply Information for smart grid (CDPS) is presented. Users need to know the power supply and price information. The consumer i reports the total power by adding the power of his neighbor. The access method used in CDPS is Time Division Multiplexing (TDM). The mechanism of CDPS consists of that in each frame, each consumer is assigned a particular time slot to transmit his own information about the power supply. However, a major disadvantage of this approach

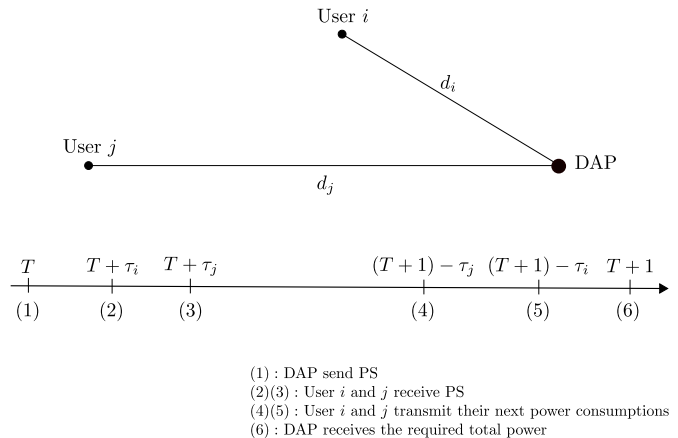


Fig. 2: Synchronization process

is that the consumer has to wait the entire frame to end to send his requests to the operator which prolongs the transmission time and causes delays.

In the cooperative scheme that we propose, the first time slot (0) is allocated to the control center to broadcast the pilot symbols, only one time, to all users for the estimation of the channel state information (CSI). After that, all the consumers start transmitting their data depending on the synchronization process explained in the next paragraph, without waiting for the frame to end as TDMA, allowing the forecasting of the needed energy for the next few minutes. In the cooperative network that we studied, the wireless communication is chosen for the transmission between costumers and the CC due to it's flexible transmission, reduced cost and complexity.

Synchronization between different users is very important to insure receiving the sum at the DAP. For our system, all users are informed in advance that the frequency of transmission of the pilot symbol (PS) is $T, 2T, \dots, nT$. First, the DAP transmits PS to all users. Due to the difference of distance between users and DAP, each user i will receive the PS with a delay denoted by τ_i . After that, each user will have to send back his own data to the DAP dependently to the delay with whom he received the PS. For instance, suppose that two users i and j with distances d_i and d_j from DAP respectively having $d_i < d_j$, i and j will receive the PS with a delay equal to $T + \tau_i$ and $T + \tau_j$ respectively. The nearest user to the DAP is the first to receive the PS and the last to transmit his data. Since the consumers i and j know beforehand that the PS is sent with a period of T , they will respond to the DAP in instants equal to $(T + 1) - \tau_i$ and $(T + 1) - \tau_j$ as shown in Fig.2, so as at the receiver, they all arrive at T which is the total time of transmission for all users.

A. Transmitter side

Each SM contains the information about the value of the power in each house. We denote the consumption power of all appliances in each house i by P_i . The received power at the level of the CC is given by: $P_t = [P_1 \dots P_N]$. To send the power P_i , which is analog, a treatment should be operated. First, we applied a quantization of 2^8 levels and a step p_u

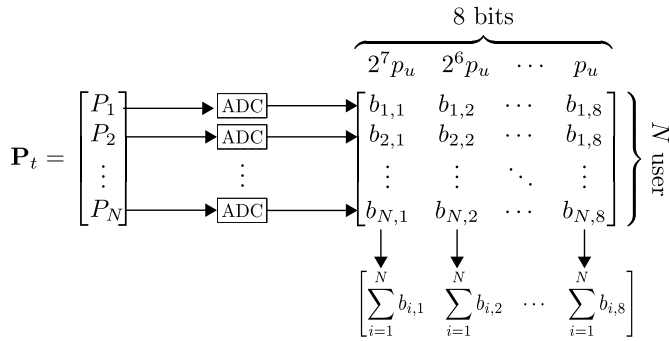


Fig. 3: The transmitted power treatment process

on P_i to get a determined number of the power to transmit. After that, we proceeded with the coding of the quantization levels to get the binary vectors b_i as shown in the Fig.3. Also, we modulated each b_i with a Binary Phase Shift Keying (BPSK) modulation. BPSK has a good noise and interference resistance and immunity. Furthermore, another treatment in the transmission side is operated in order to avoid interference and attenuation of power signal. The pre-coding method that we used allows to an access point (DAP in our case) to transmit multiple simultaneous data streams of multiple users in parallel. The concept is based on the implementation of the pseudo inverse of h_i . Our system proceeds in two phases: the steady phase and the ready phase. In the steady phase, the DAP broadcasts a pilot signal to all users in order to estimate the channel gain vector h_i , so the channel state will be known at the transmitter. The pilot signals are sent periodically which, allows the characterization of the channel at each transmission. In the ready phase, users start transmitting the data to the DAP.

By implementing the pre-coding method, the user i transmits his own data multiplied by the inverse of h_i . The pseudo-inverse of h_i is given as :

$$h_i^+ = \frac{h_i^*}{\|h_i\|^2} \quad (2)$$

From (1) and (2), we can reformulate the expression of the received signal as :

$$y = \sum_{i=1}^N \frac{x_i h_i^*}{\|h_i\|^2} h_i + n \quad (3)$$

What leads us to:

$$y = \sum_{i=1}^N x_i + n \quad (4)$$

$\sum_{i=1}^N x_i$ refers to the sum of symbols modulated with the BPSK modulation. where x_i is a BPSK modulated vector of user i which can take the value 1,-1. For the rest of our analysis, we denotes $\sum_{i=1}^N x_i = v_k$.

B. The receiver side

At the reception, we obtain the total power of all consumers. According to Fig. 3, each vector $\sum_{i=1}^N b_{ij}$ refers to the sum of x_i after the demodulation process. Each sum is a combination of the transmitted bits that depends on the number

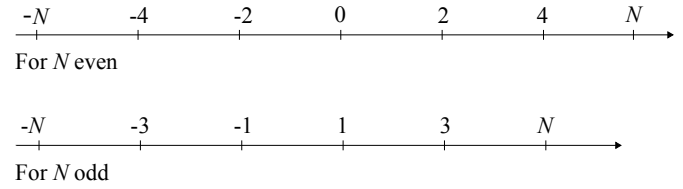


Fig. 4: Received Values for the real-time transmission

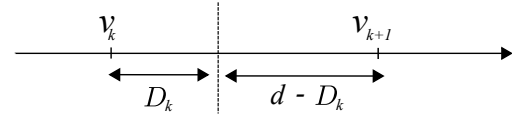


Fig. 5: Decision region for non-equiprobable symbols

of consumers. For instance, if we have N users that transmit -1 at the same time, then $\sum_{i=1}^N x_i$ equals $-N$ and b_{ij} will be then equals to:

$$b_{ij} = \frac{\sum_{i=1}^N x_i + N}{2} = \frac{v_k + N}{2} \quad (5)$$

So as to estimate the received power \hat{P}_T , according to the step p_u , we will have this expression,

$$\hat{P}_T = \sum_{j=1}^8 \sum_{i=1}^N b_{ij} \cdot 2^{j-1} p_u \quad (6)$$

For the proposed real-time scheme whether the number of users is even or odd, we get the following values as shown in Fig. 4. Since the received values don't have the same probability, it is required to have at the reception a decision system based on the hyperplane separation as shown in Fig. 5. The distance between two symbols is given by : $d = \|v_{k+1} - v_k\|$. The formula of the decision region (DR) for non-equiprobals symbols is written as,

$$D_k = \frac{d}{2} + \frac{\sigma^2 \ln(p(v_k)/p(v_{k+1}))}{d} \quad (7)$$

where σ is the noise variance relative to the Gaussian channel, and $p(v_k)$ is the probability of the values v_k . In the case of TDMA, when a single user transmits its own data, the values 0 and 1 are equiprobable, meaning that the probability equals to 1/2. As a result, the hyperplane is in the exact middle of the distance between 0 and 1. In CWT, the probability depends on the combinations of the modulated symbols possibly transmitted. The probability of v_k is then calculated as,

$$p(v_k) = \frac{C_N^{(N-k)/2}}{2^N} = \frac{N!}{((N-i)/2)!((N+k)/2)!} \cdot \frac{1}{2^N} \quad (8)$$

where k is the position of the symbol.

In fact, the DR corresponds to the multiple received values modelled as v_k points (Fig. 4). The hyperplane separation becomes closer to the value with the lowest probability. In other words, the hyperplane tends to move away from the more probable value, which increases its DR.

C. Probability of error

The probability of error (PER) is the probability when an error occurs in the received signal y while transmitting the signal v_k . We receive y and we look among all non-equiprobable v_k to find which one is the closest to y by using the decision boundaries D_k . In this case, the total value of the error probability with non-equal decision regions is given by,

$$PER = \sum_{k=-N}^N p(v_k) \int_{D_k}^{\infty} p(y|v_k) dy \quad (9)$$

where $\int_{D_k}^{\infty} p(y|v_k) dy = PER_k$ denotes the error probability of the received values for CWT scheme. The noise adopted is an Additive Gaussian Noise and PER_k has a normal distribution with variance $N_0/2$. Which leads us to a more simplified error probability expression,

$$PER_k = Q\left(\frac{D_k}{\sqrt{N_0/2}}\right) \quad (10)$$

As shown in Fig. 4, for any number of users, the extremities have the same probabilities. for example, In the case when k is an extremity, the probability of error on the value v_k equals to :

$$PER_k = \int_{D_k}^{\infty} p(y|v_k) dy = Q\left(\frac{D_k}{\sqrt{N_0/2}}\right) \quad (11)$$

For the intermediate values (Fig. 5), the error probability is calculated at the right and the left of the received value v_k . Then we have :

$$\begin{aligned} PER_k &= \int_{-\infty}^{v_{k-1}+D_{k-1}} p(y|v_k) dy + \int_{v_k+D_k}^{+\infty} p(y|v_k) dy \\ &= \left[1 - Q\left(\frac{v_{k-1} + D_{k-1} - v_k}{\sqrt{N_0/2}}\right) \right] \\ &\quad + Q\left(\frac{v_k + D_k - v_k}{\sqrt{N_0/2}}\right) \end{aligned} \quad (12)$$

(12) can simplified to :

$$PER_k = \left[1 - Q\left(\frac{-d + D_{k-1}}{\sqrt{N_0/2}}\right) \right] + Q\left(\frac{D_k}{\sqrt{N_0/2}}\right) \quad (13)$$

Using (11) and (13), the average probability of error is then equals to :

$$\begin{aligned} PER &= \sum_{k=1}^{N-1} 2 \cdot p(v_k) \cdot \left[Q\left(\frac{d - D_{k-1}}{\sqrt{N_0/2}}\right) + Q\left(\frac{D_k}{\sqrt{N_0/2}}\right) \right] \\ &\quad + 2 \cdot p(v_N) \cdot Q\left(\frac{D_N}{\sqrt{N_0/2}}\right) \end{aligned} \quad (14)$$

$$\text{where } \begin{cases} D_N = D_{-N} \\ d = v_k - v_{k-1} \\ Q(v_k) = 1 - Q(-v_k) \end{cases}$$

In the case of N even, a term depending on zero symbol should be added to (14). So, the total value of the probability of error is written as,

$$\begin{aligned} PER &= p(v=0) \cdot \left[Q\left(\frac{d - D_1}{\sqrt{N_0/2}}\right) + Q\left(\frac{D_0}{\sqrt{N_0/2}}\right) \right] + \\ &\quad \sum_{v=1}^{N-1} 2 \cdot p(v_k) \cdot \left[Q\left(\frac{d - D_{k-1}}{\sqrt{N_0/2}}\right) + Q\left(\frac{D_k}{\sqrt{N_0/2}}\right) \right] \\ &\quad + 2 \cdot p(v_N) \cdot Q\left(\frac{D_N}{\sqrt{N_0/2}}\right) \end{aligned} \quad (15)$$

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, we present the results of Matlab simulations. We consider a smart neighbor with two consumers just to simplify, but the results can be extended for any number of consumers. The metered data is aggregated at the DAP and then transmitted to the control center. The modulation scheme in the transmission is the Binary Phase Shift Keying with AWGN channel.

For the purpose of evaluation, the following table presents the adopted parameters: Based on the detection process, we

Number of samples	10^5
Number of coding bits	8
Levels of quantization	2^n
Maximum level of quantization	10
Signal power	1

TABLE I: Simulation Parameters

prove the accuracy of our analysis. Fig. 6 presents the Cooperative Symbol Error Rate (CSER) performance of the proposed scheme and the TDMA transmissions compared with the theoretical results. Where CSER refers to the error rate of the received sum of modulated symbols bi_j . The obtained results show clearly that the Cooperative Wireless Transmission for smart Grid (CWT) outperforms the TDMA in terms of CSER. Since multiple users could transmit at the same time in our model, the same noise that is added to each signal in TDMA, is added, in our case, to all users, thus reducing the probability of error. Moreover, even if the number of users increases, the performance of our scheme in terms of cooperative symbol error rate is still satisfying. To more evaluate the performance of CWT and according to (6), Fig. 7 presents the power value before and after transmission and for a given SNR. It is clear that the received power is close to the transmitted power, this means that CWT scheme improves the reliability of transmission and reduces power losses. For an SNR equals

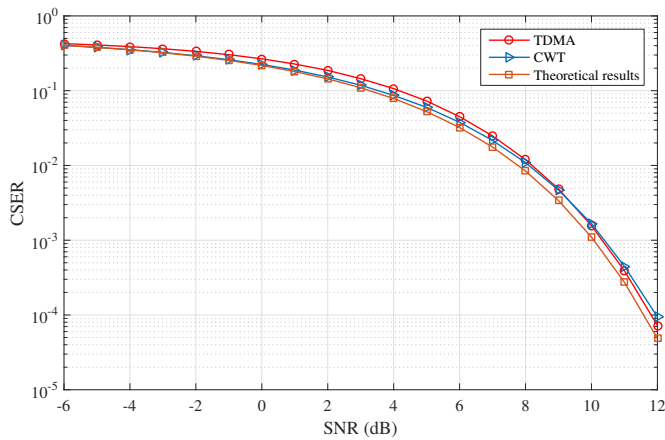


Fig. 6: CSER for two cooperative transmissions

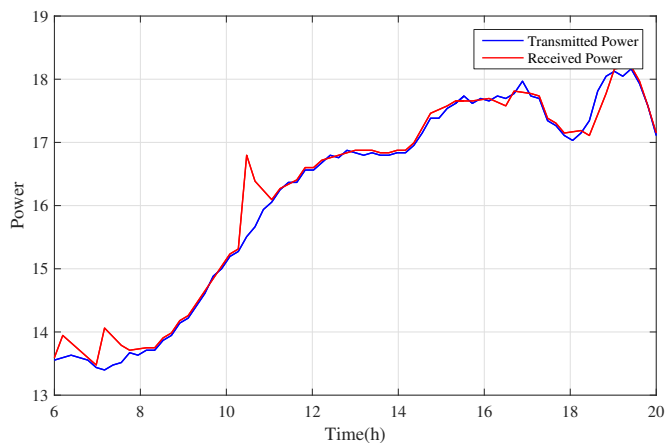


Fig. 7: Comparison between transmitted and received Power (SNR=5dB)

to 12 dB, the performance of CWT is significantly improved shown in Fig. 8. Another advantage of the proposed scheme is that all users can use the same time for transmission. Fig. 9 shows a comparison between TDMA and CWT in terms of Power Metering Delay (PMD). PMD refers to the necessary time for the DAP to determine the value of the next power consumption. For TDMA, the channel is divided into time slots that are shared with all users, each user has a predefined time-slot which means that the needed time for transmission is $N \cdot TTI$. However, for CWT, all users transmit in a period of time equivalent to only one TTI. So, the transmission time in TDMA is a linear function that depends on the number of users. But in CWT scheme, the transmission is simultaneous and the time is a constant function independently of the number of users.

V. CONCLUSION

In this paper the performance of a Cooperative Wireless Transmission of Smart Metering (CWT) scheme for smart grid communication infrastructure, for NAN, have been evaluated. The aim is to gather the total of power demand from all the consumers and convey it simultaneously, for time saving, to the DAP in a wireless link by using a special pre-coding in

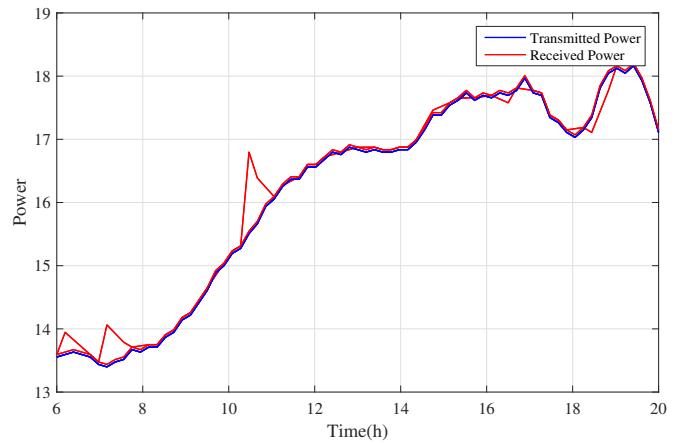


Fig. 8: Comparison between transmitted and received Power (SNR=12dB)

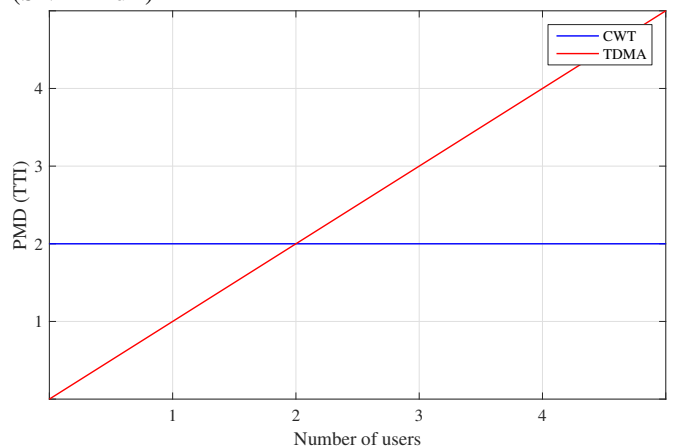


Fig. 9: Transmission duration for TDMA and CWT schemes

the transmitter side. Our model is also cooperative in terms of resistance to noise. Since the noise that is usually added to one user's signal, is in our case, divided on all consumers which makes it more immune from errors. We have evaluated the proposed scheme in terms of CSER by using BPSK modulation and compared to TDMA, the results are certainly satisfying.

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