Distributed Framework for Cognitive Radio Based Smart Grid and According Communication/Power Management Strategies

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Abstract. This paper analyses the smart grid's facing challenges and the features of new energy source, then proposes the distributed frameworks for Cognitive Radio based Smart Grid (CRSG) on Home Area Network (HAN), on Neighbour Area Network (NAN), and on distributed power generators respectively. The basic protocols such as the communication protocols of cognitive radio networks, power transmission protocols among different users, and power transmission protocols between users and distributed power plants are presented. Those protocols are evaluated in the proposed distributed CRSG with network simulation platform, and the results show that distributed framework is economic and effective.

Keywords: Smart grid · Cognitive radio networks · Distributed networks · Power grid · Resource allocation

1 Introduction

Smart grid takes advantage of the advancement in communication and control technologies to create an automated, widely distributed delivery network through the use of bidirectional connection of electricity and information flows [1]. Global demand for renewable energy in distribution grids continues to rise and the worldwide installed capacity of PV exceeded 139 GW in 2013 [2,3], a total of approx. 200 GW PV capacity is to be installed by 2050. To reach this amount by 2050, an average of 4–5 GW PV must be installed annually in Germany.

In SG network, because the explosive data transmission demand, the centralized framework face very heavy burden, distributed infrastructure and according communication/power transaction protocol became the most hot research spot recently. Authors in [5] propose a simulation framework for distributed intelligent grid system. [6] describes the overall architecture of a monitoring system for distributed generation infrastructures of the Smart Grid, as well as the developed pieces of hardware and software, in addition, the validation of the system is also outlined. [7] uses two types of scalable distributed communication architectures, communication architecture with distributed meter data management

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system (MDMS) and fully distributed communication architecture to minimize the deployment cost. [8] proposes a distributed, service-oriented control architecture which provides a generic framework that could support numerous smart grid applications. [9] considers an interaction system of the smart grid, which including the cloud computing system and load devices, moreover, the authors propose a nested game-based optimization framework. In [10], the authors investigate the scalability of three communication architectures for advanced metering infrastructure (AMI) in smart grid, formulate an optimization problem and obtain the solutions for minimizing the total cost of the system that considers both the accumulated bandwidth distance product and the deployment cost of the MDMS.

To save the communication cost and avoid the message delivery failure of power line communication (PLC), wireless cognitive radio is a good technology of smart grid. Centralized CRSG infrastructure is easy to create but not suitable for accessing numerous of user-side power generators, Fig. 1 shows the traditional centralized CRSG infrastructure, where HAN is the basic local network connected with different home applications and smart devices, HAN collect the demands/status parameters of home applications and smart devices, each HAN has one gateway named HGW, numbers of HGWs construct the Neighbour Area Network (NAN), each NAN has a gateway named NGW, the collected parameters will be delivered to the control center (CC) through HGW, NGW and CR base station.

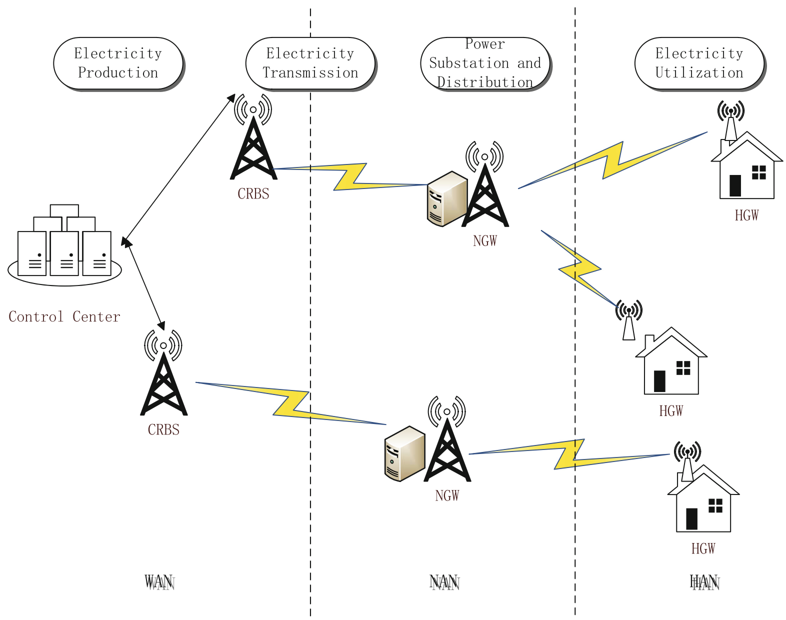

Fig. 1. Centralized CRSG

For the centralized CRSG infrastructure, along the dramatic increasing of data/command communication demand, the burden of CC face big challenge, at the same time, it is not convenience to access user-side distributed power generator, in this paper, we propose a flexible distributed network framework to try to solve those problems, and according communication/power transaction protocols are studied.

2 Distributed CRSG Framework

2.1 Distributed Framework in HAN

In the future of the smart grid, new energy access is the undoubted trend, many countries around the world have the user side new energy access plan, such as Germany's millions of roof plan, solar power systems and smart meters are installed on the user's roof, photovoltaic power generation send power to the grid in the day time and recharge the balance for user's smart meter, in the night, users can buy power from the grid and the balance will be charged.

In the distributed framework in CRSG HAN, the wireless communication and power transmission all are distributed. CR technology allow the CR spectrum can be used by CR based electronic users, and distributed CR network release the heavy burden of control center, the designed distributed network architecture can be seen as Fig. 2. We assume each user has one energy storage, and the Data Aggregation Unit (DAU) is the sink node of a HAN.

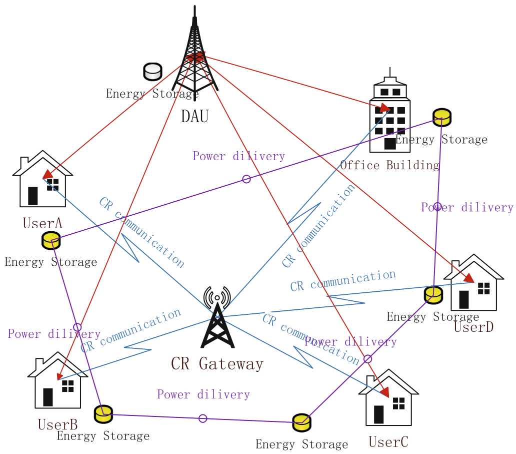

Fig. 2. Distributed framework in HAN

2.2 Distributed Framework in NAN

The distributed infrastructure in NAN can be seen as Fig. 3, different from the centralized infrastructure, we assume each HGW has one DAU and a wireless transmission equipment, HGW can collect the data from user smart meters, communicate with other DAUs/NGWs, and send command for power transmission. NAN support the last mile communication service for smart grid, that is, DAU manage all the data of its covered HAN. In our design, we let different DAU can communicate with each other and translate power with each other, then some times the communication and power interaction between them can be successful without the management of CC.

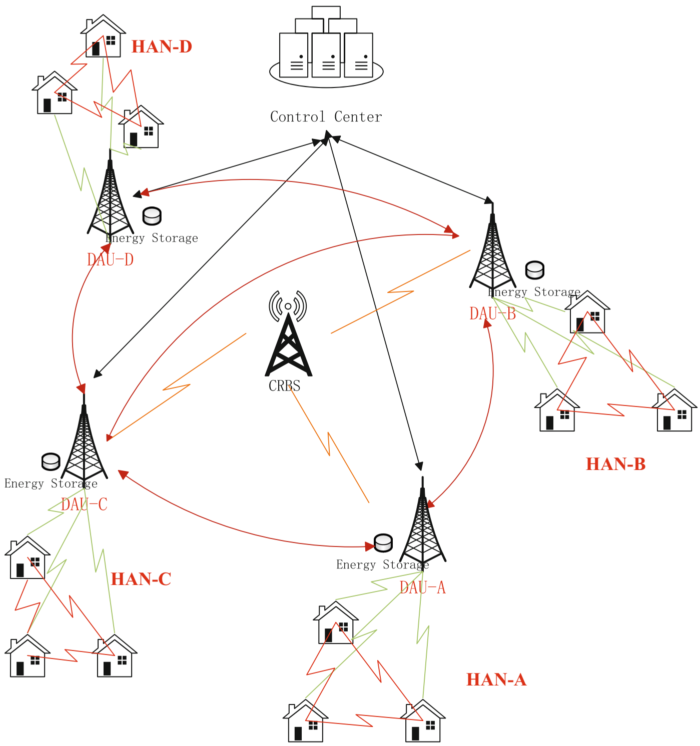

Fig. 3. Distributed framework in NAN

2.3 Framework of Distributed Power Generators

The combination of renewable energy and power grid is an important improvement of the smart grid. Use of renewable energy power generation can be a form of distributed matte or a centralized form. Centralized power generation usually makes unified scheduling directly connected to the transmission grid, for example, large-scale wind field, large-scale photovoltaic power station with MW/GW level. While distributed generation is usually connected to the low voltage distribution network, such as 380 V or 10 kV distribution power network. Distributed generation has the most important features of environmental protection, energy saving and efficient. So the modern smart grid should have good incompatibilities for centralized power, distributed generation, renewable energy access and energy storage device. Distributed generation is the future development direction of power system, the future of the power supply should be the hybrid network of the centralized and distributed grid.

Distributed generation has a key factor of energy storage, this is the bottleneck restricting the distributed power generation. Currently the battery energy storage is the most popular if the storage problem is resolved, electricity two-way flow in the smart grid is possible. Energy storage devices can provide power supply in peak period to reduce the peak lever, and sell power to other users/power company if possible.

As is known to all, renewable energy generally has the following several types, photovoltaic power generation, wind power, small hydropower, geothermal, ocean wave force power, solar thermal power generation, fuel cell power generation, etc. Renewable energy has the biggest characteristic of distributed geographical position, it's hard to uniformly control and manage all the renewable energy, as a result, the distributed management and self-control will be more reasonable, At the same time, because of the distributed energy dispersion and the randomness of the distributed generation, if adopting the fixed frequency allocation in according communication network, the usage of spectrum resources will be inefficient, so CR is a efficient and economy communication technology in such smart grid.

Based on the above analysis, after joining the distributed power, the designed distributed network architecture can be found as Fig. 4. The renewable energy can be saved in energy storage and can be controlled by CR based SG.

3 Communication and Energy Delivery Protocols

3.1 CR Communication Protocol

We adopt the basic CR communication mechanism in this paper, each communication node listens the wireless interference at any time, its communication will fail only if its occupying channel is recycled by a new coming primary user.

3.2 Communication and Power Transmission Protocol Among DAUs

From the distributed NAN architecture, assuming that the area which contains DAU-A has a lot of demand for electricity, the DAU-A will send electricity demand message to other DAUs, by responding message from other DAUs, DAU-A select the DAU-B which is close to DAU-A and has reasonable price as the

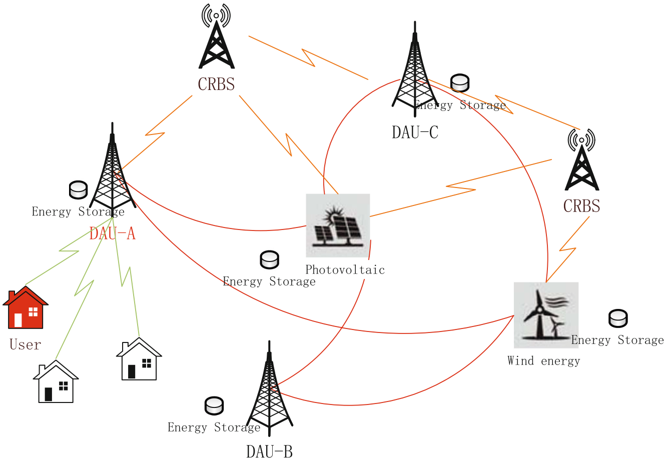

Fig. 4. Framework of distributed power generators

transaction object, so DAU-A sends a purchase request directly to DAU-B. This protocol not only reduces the power transmission distance, transmission costs, but also increases the response speed, this protocol can be seen as Fig. 5.

```
=========================================================
while (not time out)
A broadcasts energy requirement
if (received replay ){
   if (find a energy unit seller B){
      send transaction requirement to B
      if (receive transaction acknowledgement from B){
          power transition between A and B
      }
   } else
      buy energy from power company
}
=========================================================
```

Fig. 5. Communication and power transmission among DAUs

3.3 Communication and Energy Transaction Protocol with Distributed Power Plant

In a HAN, if a user's (say user A) electricity consumption demand increases dramatically during the power consumption peak periods, at this time, if A get power directly from the main power grid, usually the cost is high. For the protocol of considering distributed power plant, DAU-A send power requirement to other DAUs through cognitive radio technology and wait reply, on the other hand, all the DAUs which received DAU-A's power demand will reply if its energy storage is enough, DAU-A will select the best one for transaction, the protocol is illustrated in Fig. 6.

```
=========================================================
while (not time out)
DAU send energy requirement to distributed power plant
if (received replay ){
   select the optimal energy source seller B
   while ((B exist) && (not receive ACK from B)){
      send transaction requirement to B
      if (receive transaction ACK from B){
          power transition between A and B
      }
   } else
      buy energy from power company
}
=========================================================
```

Fig. 6. Communication and energy transaction protocol with distributed power plant

4 Performance Analysis

Under the distributed CRSG framework described before, we create a discrete time driven simulation platform with ns-3 [11] to evaluate the performance of the network with different CR resource allocation and power transaction protocols.

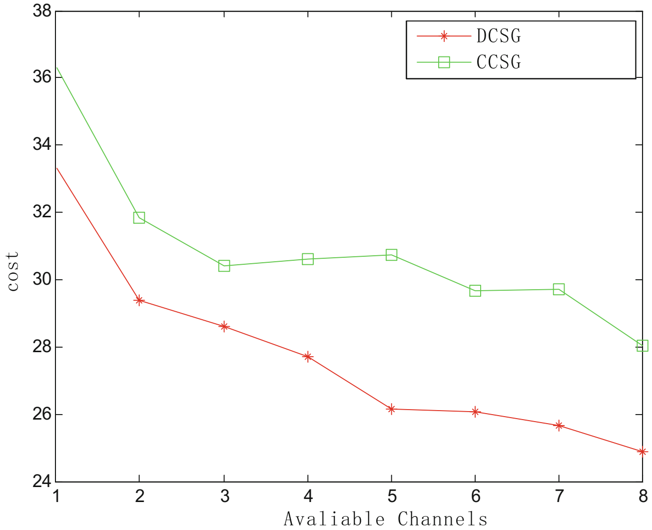

Fig. 7. User cost and available CR spectrum

The simulation parameters are set as follows, there are three NGWs, each NGW has three HGWs, the number of distributed power plant is 10, time-out threshold is in [0.1, 0.8], the number of available spectrum is in [1,8], the price of power grid is set to 0.5/kW, the path loss coefficient is from 0.2 to 0.9, the price of distributed power plant is normally distributed between [0.2, 0.5].

Figure 7 shows that users' cost decreases with the increasing of the number of available spectrum. With the increase of the available spectrum, the probability of a user get CR spectrum for transmission before time out increases, so lager probability users can exchange power from each other, because normally users' transaction price is lower than that of power company, so the users' average electricity cost will be reduced. So under the same number of available CR spectrum, users' cost in distributed cognitive radio smart grid (DCSG) is less than that in centralized cognitive radio smart grid (CCSG).

Figure 8 shows that with the time-out threshold increases, user cost will reduce. because in the spectrum allocation procedure, to avoid the long waiting time for spectrum allocation, if the waiting time exceeds the time-out threshold, the user will purchase power from the power grid. If the threshold is high, the users' waiting time became long, and the probability of users purchase power from distributed other users increases, which leads their cost decrease.

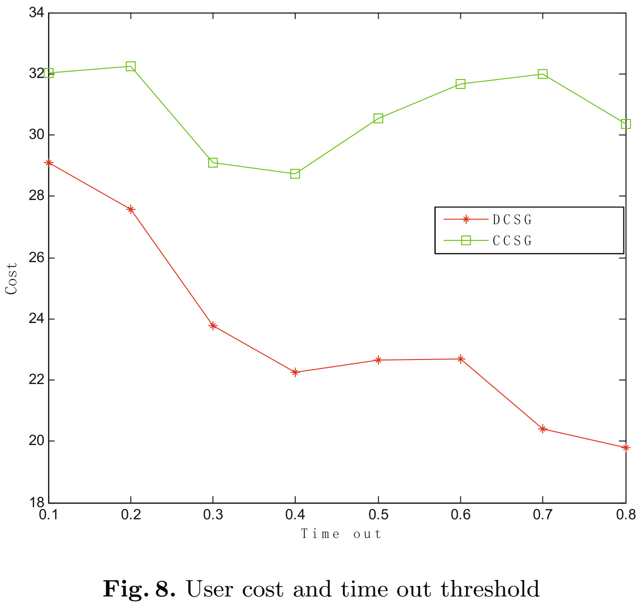

Fig. 8. User cost and time out threshold

Figure 9 shows that with the increase of path loss, user cost will increase, because under the situation, more power will be purchased from the grid company. Compare with the centralized network, distributed infrastructure and according protocols can save users' cost significantly.

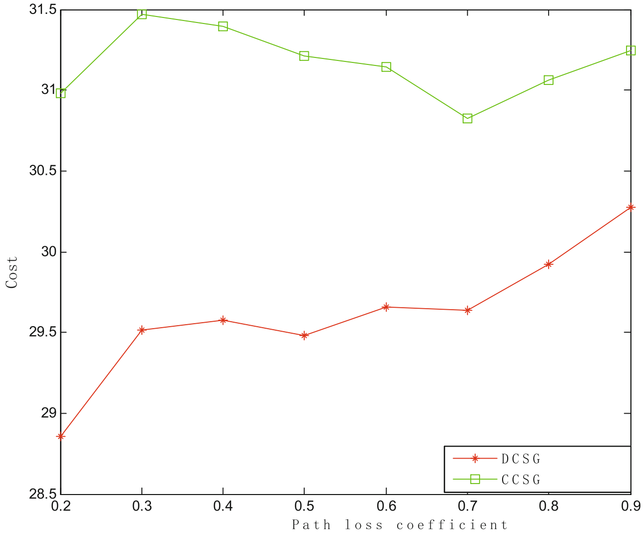

Fig. 9. User cost and path loss coefficient

5 Conclusions

In this paper, we propose the distributed frameworks of cognitive radio based smart grid, the distributed scenarios include the distributed framework in HAN, distributed framework in NAN, and distributed framework of distributed power generators. The communication protocols and power transmission protocols are also presented, and the simulation show that the distributed network and according protocols is very economic and effective.

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