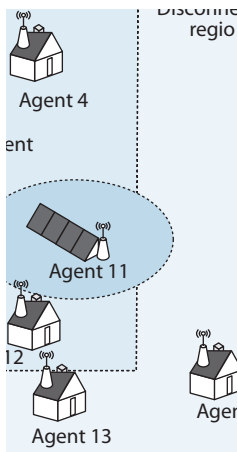


# MULTIAGENT COORDINATION IN MICROGRIDS VIA WIRELESS NETWORKS

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The authors present a consensus theory based multiagent coordination scheme for information discovery in microgrids via wireless networks. The information discovery process is fully distributed such that each agent only needs to communicate with its direct neighbors.

## ABSTRACT

The future smart grid is expected to be an integration of intelligent microgrids featured by localized electricity generation, storage, and consumption. Wireless communication is a promising means to facilitate pervasive microgrid monitoring and control at a high flexibility and low deployment cost. In order to avoid a single point of failure, multiagent system (MAS) based decentralized microgrid control is widely considered. In this article, we present a consensus theory based multiagent coordination scheme for information discovery in microgrids via wireless networks. The information discovery process is fully distributed such that each agent only needs to communicate with its direct neighbors. The multiagent coordination is investigated in the presence of interference due to wireless transmissions. Specifically, the communication links among multiple agents may not be established simultaneously to avoid transmission collisions. In order to assure the accuracy of the information discovered by each agent, the convergence of the multiagent coordination is studied. We present the mechanism and principles for the multiagent coordination to achieve convergence in a microgrid via wireless network based on the characteristics of the information to be discovered. Three protocols with different complexities are proposed for normal microgrid operation, which can be readily implemented to off-the-shelf wireless communication devices. The protocols are further extended to achieve microgrid fault recovery by restricting the information exchange in a disconnected region to improve recovery speed. The performance of the proposed protocols is evaluated via a case study based on the network topology and configuration of a realistic microgrid test system. Open research issues and directions are outlined.

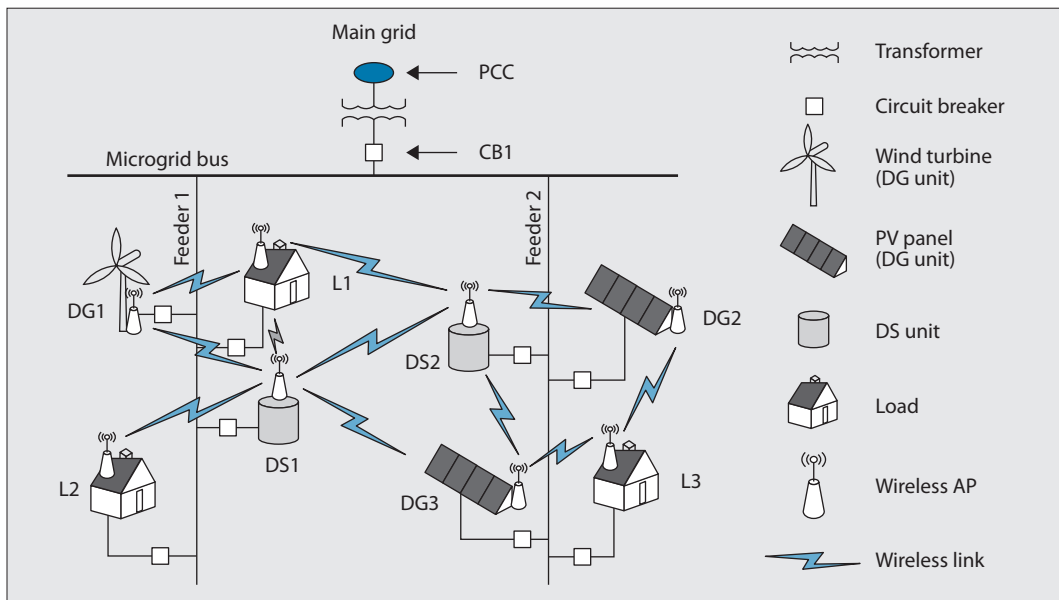
## INTRODUCTION

Towards the gradually depleting fossil fuels, increasing energy costs, and worsening environmental conditions, an upgrade in the current elec-

trical power system is indispensable to incorporate more distributed energy resource (DER) units, such as the distributed generation (DG) units and distributed storage (DS) units [1]. The DG units utilize renewable energy sources such as photovoltaic (PV) panels, wind turbines, and combined heat and power (CHP) systems. As the DER units typically operate at a distribution voltage level and geographically close to loads, microgrids are developed to interconnect the energy sources and loads in a relatively small area, such as a suburban community, a university or school, a commercial area, and an industrial site. Besides the environmental benefit of using more renewable energy sources, a microgrid can be either tied to the main grid as a single aggregated load (or generator) or islanded as a self-sustained power system, which significantly simplifies the main grid control by the utilities. From the customers' point of view, the energy cost can be reduced by increasing the usage of sustainable energy and decreasing the transmission and distribution energy losses taking advantage of the physical proximity of energy sources and loads.

Despite the potential benefits of microgrids, how to achieve pervasive monitoring and control over a large number of plug-and-play DER units and loads is very challenging. The next generation power grid, also known as the smart grid, is expected to utilize the state-of-art information and communication technology to address this challenge [2]. Wireline and wireless networks are two potential candidates for the communication infrastructure of a microgrid [3]. Compared with the wireline counterpart, a wireless network has the advantage of high flexibility and low deployment cost, which perfectly fits the plug-and-play nature of microgrids with a large number of DER units and loads in a relatively small local area. For instance, in a remote rural area where most of the renewable DER units are located, a fiber-optic wireline network is less cost-effective as compared with a WiFi or ZigBee based wireless network [1, 2].

Based on the communication network infrastructure, both centralized and decentralized control can be established for a microgrid.



**Figure 1.** Network topology of a microgrid.

Specifically, the decentralized control does not need a powerful central controller and is resistant to the single failure point. Various research has been done for the decentralized microgrid control, and the multiagent system (MAS) based approach is a prime candidate [3]. Each DER unit or load is considered as an agent which has the intelligence of making local decisions by acquiring information from some of the other agents. In order for the local decisions to be accurate, global information should be discovered by each agent with a certain accuracy via multiagent coordination. In this article, we investigate a consensus theory based multiagent coordination scheme [4], which has the following advantages:

- Communications need to be established only among the neighboring agents, and the computational complexity of information update is low. The proposed protocols can be easily applied to off-the-shelf wireless communication devices (e.g., WiFi and ZigBee based devices) with limited transmission range and computational power;
- The convergence of global information discovery can be guaranteed, which ensures that all agents can acquire the desired information to provide reliable decentralized control in a microgrid;
- The convergence speed can be evaluated analytically, which can facilitate the planning and optimization of the communication network infrastructure of a microgrid.

In comparison with the data dissemination schemes in sensor networks such as directed diffusion [5], the consensus theory based multiagent coordination scheme is more suitable for decentralized control in microgrids since there is no central controller (or sink node) to collect the network-wide information and make overall decisions accordingly. Moreover, the performance metrics with respect to the entire microgrid (i.e., the total generation, consumption, and net power) can be intrinsically calculated during the multiagent coordination procedure, which

simplifies the protocol design for the agents with low-cost wireless communication devices. However, for the communications over a broadcast medium, wireless network is subject to interference, which makes the information exchange unreliable. Multiagent coordination in a microgrid via power line communications [4] has been investigated without interference among different links. For a wireless network where this assumption can hardly be valid, how to achieve efficient and reliable multiagent coordination in a microgrid is still an open issue.

In this article, we present the mechanism and principles for a multiagent coordination scheme to achieve fast convergence in a microgrid via wireless communications. Specifically, the state values of the information discovered by all agents in a microgrid converge to a single value in a timely manner. Several protocols with different complexities are proposed, which can be readily applied to off-the-shelf wireless communication devices. The protocols are further extended to achieve efficient fault recovery in a microgrid. The performance of the proposed protocols is evaluated via a case study based on a realistic microgrid test system. Future research topics are also outlined.

## NETWORK TOPOLOGY AND INFORMATION REPRESENTATION

The network topology of a typical microgrid is shown in Fig. 1 [1, 3]. The microgrid is coupled with the main grid (i.e., utility grid) via a point of common coupling (PCC). The microgrid can operate either in a grid-connected mode or in a stand-alone mode based on the operation of circuit breaker CB1. Without loss of generality, we consider the stand-alone mode in this article with an opened CB1. There are two feeders in the microgrid to supply the electrical loads. Feeder 1 has two loads (i.e., two households), a DG unit (i.e., a wind turbine), and a DS unit, while feeder

Based on the communication network infrastructure, both centralized and decentralized control can be established for a microgrid. Specifically, the decentralized control does not need a powerful central controller and is resistant to the single failure point.

For typical applications in a microgrid such as load restoration, load shedding, and island identification, there are generally two types of information to be discovered which can be represented by different kinds of state values: Type 1 - status Information and type 2 - performance metric,

2 has two DG units (i.e., two PV panels), a load, and a DS unit. Each element in the microgrid (including load, DG unit, and DS unit) is equipped with a wireless access point (AP). According to the MAS architecture, each AP along with the microgrid element connected to it is called an agent in the network [3]. The wireless links are considered to be bidirectional. Because of a limited transmission range, each agent can only communicate with a group of neighboring agents. For instance, in Fig. 1, agent L1 can communicate with agents DG1, DS1, and DS2, while agent DG3 can communicate with agents DS1, DS2, and L3. For notation simplicity, we assign each agent a unique ID within the set  $A = \{1, 2, \dots, Q\}$ , where  $Q$  is the total number of agents. For instance,  $Q = 8$  for the microgrid shown in Fig. 1. We consider homogeneous wireless devices with a fixed transmission rate and a transmission range equal to the interference range. Denote the group of neighbors of agent  $m$  ( $m \in A$ ) as  $N_m$  ( $N_m \subseteq A \setminus \{m\}$ ). A transmission of agent  $m$  can interfere with another transmission to agent  $n$  if and only if  $n \in N_m$ , which results in an unsuccessful reception at agent  $n$ .

For typical applications in a microgrid such as load restoration, load shedding, and island identification [4], there are generally two types of information to be discovered which can be represented by different kinds of state values.

**Type 1) Status Information:** The status information is defined for each agent and the state value is binary, i.e., fault or unfaulted. An agent in a fault status cannot perform its typical functionality (e.g., power generation for a DG unit), and vice versa.

**Type 2) Performance Metric:** The performance metric can be defined for each agent or for the entire microgrid, and the state value corresponds to the actual performance measure. Specifically, the performance metrics of the entire microgrid include the total generation, consumption, and net power, which are, respectively, the summation of the corresponding local performance metrics, i.e., the local generation, consumption, and net power of each agent.

Consider the information discovery processes for two kinds of microgrid operation modes, i.e., normal operation and fault recovery. For normal operation, the local information is periodically generated by each agent. The duration of each period is  $T$ . Within  $T$ , each agent should discover the global information via information exchange with neighboring agents and then make the local decision. Without loss of generality, consider a tagged piece of information generated at time  $t_0$  with initial state value  $x_m(t_0)$  for agent  $m$  ( $m \in A$ ). Let  $X(t) = (x_1(t), x_2(t), \dots, x_Q(t))^T$  be the vector of the discovered state values, where  $x_m(t)$  represents the state value kept by agent  $m$  at time  $t$ , and  $(\cdot)^T$  denotes the transpose operation. Suppose  $T$  is sufficiently large. The global information discovery process converges if  $x_m(t) \rightarrow x^*$  as  $t \rightarrow \infty$  for all  $m \in A$ , where  $x^*$  is the state value of the discovered global information. In other words, all agents in the network can eventually obtain the same state value of the information, which ensures that an accurate decentralized microgrid control such that the same local decision can be made by all agents.

For different types of information, the initial state values ( $x_m(t_0)$ ,  $m \in A$ ) are defined in different ways. For the status information of a specific agent  $m$ , the initial value at agent  $m$  is given by  $x_m(t_0) = 1$  and  $x_m(t_0) = -1$  for fault and unfaulted status, respectively. For any other agent  $n$  ( $n \neq m$ ), let  $x_n(t_0) = 0$  since the status of agent  $m$  is unknown a priori. After the information discovery process, if the state value kept by agent  $n$  ( $n \in A$ ) is positive, i.e.,  $x^* > 0$ , agent  $n$  considers the status of agent  $m$  as fault, and vice versa. Note that the actual value of  $x^*$  is not important since the positivity/negativity is sufficient to determine the status of an agent. For the performance metric, if the information to be discovered is with respect to the entire microgrid, let the initial value  $x_m(t_0)$  be the local performance metric of agent  $m$  ( $m \in A$ ). On the other hand, if the information to be discovered is with respect to a specific agent  $n$ , let  $x_n(t_0)$  be the local performance metric of agent  $n$ , while  $x_m(t_0) = 0$  for any other agent  $m$  ( $m \in A$ ,  $m \neq n$ ) since the performance metric of agent  $n$  is unknown a priori. After the information discovery process, the state value  $x^*$  kept by each agent corresponds to the actual performance measure with respect to the entire microgrid or a specific agent, respectively.

Whenever a fault occurs, the microgrid enters the fault recovery mode. The protection system immediately opens a few circuit breakers to disconnect (or isolate) a few agents close to the fault while keeping the other agents in normal operation. Thus, the microgrid can be considered as being partitioned into two regions, i.e., the disconnected region and unfaulted region which include the disconnected agents and normal operating agents, respectively. Then, an information discovery process is performed to discover the excessive generation (i.e., the redundant power not used by the loads) in the unfaulted region and the loads which are ready for recovery in the disconnected region. The load estimation is completed by the power system itself and is assumed to be accurate. If the excessive generation is positive, the redundant power can be used to restore some of the loads in the disconnected region by closing the opened circuit breakers. The decision on load restoration, i.e., whether or not to close the circuit breaker of a disconnected agent, is made locally by each disconnected agent based on the discovered information. The global information discovery process is similar to that of the normal operation, while the process is performed once instead of periodically. As soon as the fault recovery process is completed, the microgrid returns to the normal operation mode.

## MULTIAGENT COORDINATION

The theoretical foundation of the multiagent coordination scheme is the consensus theory [6, 7]. The performance of a multiagent coordination scheme is determined by two factors, i.e., the convergence and convergence speed. The convergence ensures that each agent in the microgrid has the same state values for the status information and performance metric of each agent and/or the entire microgrid to make local decisions. Fur-

thermore, the convergence should be achieved as soon as possible for a timely decision making. In this section, we first present the mechanism of multiagent coordination in a microgrid via wireless communications and summarize the conditions of convergence. Then we investigate how to improve the convergence speed.

### MECHANISM

Suppose the update of state values takes place at time steps  $t_1, t_2, t_3, \dots$ . For the  $k$ th step, let  $M(t_k)$  denote the group of agents involved in the update. Agent  $m$  ( $m \in M(t_k)$ ) acquires the state values kept by a group  $\tilde{N}_m(t_k)$  of neighboring agents via information exchange, where  $\tilde{N}_m(t_k) \subseteq N_m$  since the wireless links may not be established simultaneously to avoid transmission collisions. Then the state value kept by agent  $m$  is updated based on a weighted average of the acquired state values, given by

$$x_m(t_k) = \begin{cases} \sum_{n \in \tilde{N}_m(t_k) \cup \{m\}} \omega_{mn}(t_k) x_n(t_{k-1}), & \text{if } m \in M(t_k) \\ x_m(t_{k-1}), & \text{if } m \in A \setminus M(t_k) \end{cases} \quad (1)$$

where  $\omega_{mn}(t_k) \geq 0$  is the weight used by agent  $m$  with respect to agent  $n$ . Note that the group of agents which are not involved in the information update at time  $t_k$  (denoted by  $A \setminus M(t_k)$ ) is also included in Eq. 1 for presentation clarity. Denote the weight matrix of the update at time  $t_k$  as  $W(t_k) = [\omega_{mn}(t_k)]_{|A| \times |A|}$  such that  $X(t_k) = W(t_k) X(t_{k-1})$ . Let directed graph  $G(t_k) = (A, E(t_k))$  represent the communication pattern of the update at time  $t_k$ , where  $E(t_k)$  is an edge set with  $(n, m) \in E(t_k)$  if  $\omega_{mn}(t_k) > 0$ , which indicates that the update of agent  $m$  at time  $t_k$  utilizes the state value acquired from agent  $n$ .

### CONDITIONS OF CONVERGENCE

For presentation clarity, we first define a set of conditions with respect to the weight matrix  $W(t_k)$  and communication pattern  $G(t_k)$  as follows:

- C1: The weight matrix  $W(t_k)$  is a row stochastic matrix, i.e., each row of  $W(t_k)$  sums to 1
- C2: The weight matrix  $W(t_k)$  is a doubly stochastic matrix, i.e., each of the rows and columns of  $W(t_k)$  sums to 1
- C3: The graph  $(A, \cup_{k \geq j} E(t_k))$  is strongly connected for any  $j \geq 1$
- C4: The wireless communication is bi-directional, i.e., if  $(n, m) \in E(t_k)$ , then  $(m, n) \in E(t_k)$
- C5:  $(n, m) \in E(t_k)$  infinitely often, i.e., there exists some  $B$  such that  $(n, m) \in E(t_k) \cup E(t_{k+1}) \cup \dots \cup E(t_{k+B-1})$  for any  $k \geq 1$

According to the consensus theory, the conditions for the convergence of status information and performance metric are different. Intuitively, more conditions should be satisfied by the multiagent coordination scheme with respect to the performance metric since the discovered state value should be equal to the actual performance measure. Specifically, in order for the status information discovery process to converge, the condition set  $\{C1, C3, C4\}$  or  $\{C1, C3, C5\}$  should be satisfied. In other words, C1 and C3

are the basic conditions of convergence. If bi-directional wireless communications (with respect to C4) cannot be established for each update, C5 guarantees a bounded information exchange delay. On the other hand, for the convergence of performance metric discovery process, the condition set  $\{C2, C3, C4\}$  or  $\{C2, C3, C5\}$  should be satisfied, where C2 guarantees that the average consensus can be asymptotically reached, i.e.,  $x^* = 1/Q \sum_{m=1}^Q x_m(t_0)$ . Therefore, the actual performance metric is given by  $Qx^*$  based on the information representation.

### WEIGHT MATRIX DESIGN

According to the consensus theory, the second largest eigenvalue of the product of weight matrices (i.e.,  $\prod_{k \rightarrow \infty} W(t_k)$ ) determines the convergence speed. In a microgrid where all wireless links (each connecting two neighboring agents) likely cannot be active simultaneously to avoid interference, the convergence speed is determined by two factors, i.e., the medium access control (MAC) delay (i.e.,  $t_k - t_{k-1}$  for the  $k$ th update with  $k = 1, 2, 3, \dots$ ) and the intrinsic benefit of each graph  $G(t_k)$  which affects the second largest eigenvalue [8]. As the optimal weight matrix design is still an open issue for wireless networks, we introduce two types of weight matrices which utilize the minimum and maximum numbers of wireless links for each step of information update, referred to as pairwise average and Metropolis method, respectively. The two types of weight matrices only involve low-complexity calculations, which is suitable for the implementation based on low-cost wireless communication devices.

**Pairwise Average** — Each update of state values involves two neighboring agents [6]. At time  $t_k$ , suppose  $M(t_k) = \{m, n\}$ , where  $n \in \tilde{N}_m(t_k)$  and  $m \in \tilde{N}_n(t_k)$ . After the information exchange between the two agents, each agent calculates an average based on the state value obtained from the other agent, i.e.,  $\omega_{nm}(t_k) = \omega_{mn}(t_k) = \omega_{mm}(t_k) = \omega_{nn}(t_k) = 1/2$  for the agents in  $M(t_k)$ . Although the convergence speed is not maximal, the pairwise average provides a simple way to achieve convergence in multiagent coordination, especially for applications which are relatively time-insensitive.

**Metropolis Method** — The Metropolis method exploits the number of neighbors of each agent to provide a fast convergence in multiagent coordination [4]. Each update involves all agents in  $A$  and the update of a specific agent  $m$  ( $m \in A$ ) utilizes the state values acquired from all neighboring agents (i.e.,  $\tilde{N}_m(t_k) = N_m$ ). The weight matrix is time-invariant (i.e.,  $W(t_k) = W$ ) with the elements given by

$$\omega_{mn} = \begin{cases} \frac{1}{\max(|N_m|, |N_n|) + 1}, & \text{if } n \in N_m \\ 1 - \sum_{j \in N_m} \frac{1}{\max(|N_m|, |N_j|) + 1}, & \text{if } n = m \\ 0, & \text{otherwise.} \end{cases} \quad (2)$$

The global information discovery process is similar to that of the normal operation, while the process is performed once instead of periodically. As soon as the fault recovery process is completed, the microgrid returns to the normal operation mode.



The rationale of using the unicast mode is to guarantee the reliability in information exchange since the multiagent coordination cannot achieve convergence if some information is lost because of wireless transmission errors.

To implement the Metropolis method in a microgrid, the wireless links for each update may be active sequentially to avoid interference.

Since the weight matrix design is predetermined for both pairwise average and Metropolis method, the intrinsic benefit of a specific update in the network is fixed. To further increase the convergence speed of the multiagent coordination scheme, the MAC delay in terms of  $t_k - t_{k-1}$  ( $k = 1, 2, 3, \dots$ ) should be reduced, to be discussed in the following section.

## PROTOCOL DESIGN FOR NORMAL OPERATION

In this section, we propose several protocols for the normal operation of a microgrid. Without loss of generality, we consider the IEEE 802.11 based wireless devices with a unicast communication mode such that each data transmission is followed by an ACK message. The rationale of using the unicast mode is to guarantee the reliability in information exchange since the multiagent coordination cannot achieve convergence if some information is lost because of wireless transmission errors. A reliable broadcast mechanism (currently not supported by the IEEE 802.11 MAC) should improve the efficiency of the multiagent coordination scheme.

The protocols are introduced in an increasing order of computational complexity. The first two protocols, pairwise average and update-and-wait/update-and-continue, are based on the IEEE 802.11 MAC. In order to improve the efficiency of information exchange by reducing the MAC delay, we further propose a deterministic scheduling scheme which exploits the fixed topology of a microgrid and utilizes a time division multiple access (TDMA) based scheduling scheme.

### PAIRWISE AVERAGE

The weight matrix design is based on the pairwise average. Each agent randomly selects one of its neighbors to send the state values kept by itself, while the receiver agent replies its own state values in the next transmission opportunity. After the information exchange, a pairwise average is performed by both agents based on the received state values. For each agent, the information update is processed in a first-come-first-serve manner. In other words, if another agent sends its own state values to either of the two agents before their information exchange is completed, the receiver agent keeps the newly received state values and replies the sender after the current update is completed. For random access based on the IEEE 802.11 MAC, the convergence of the pairwise average protocol is achieved with certain probability since the wireless links are established opportunistically.

### UPDATE-AND-WAIT/UPDATE-AND-CONTINUE

The update-and-wait protocol operates in a synchronous manner and is similar to the protocol proposed for wireline networks [4]. The weight matrix design is based on the Metropolis method. After each update, an agent waits until the next iteration begins, where an iteration cor-

responds to the completion of an update of all agents in the network. For the random access with IEEE 802.11 MAC, the duration of each iteration becomes a random variable. In order to ensure the convergence of the multiagent coordination scheme, a worst-case waiting time (which equals the maximum duration of an iteration) should be used to guarantee that all agents complete their updates before the next iteration begins, which is the main drawback of the update-and-wait protocol in a wireless environment.

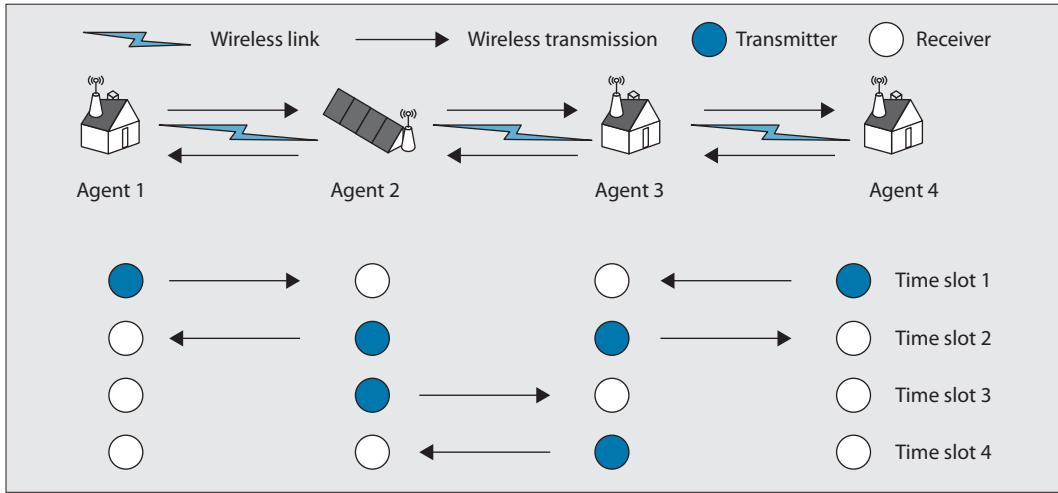
In order to overcome the limitation, we propose an update-and-continue protocol. Instead of waiting until the information update is completed by all other agents, each agent starts to transmit the updated information to its neighbors whenever a local update is completed. The neighboring agents store the received information and use it for the next update whenever the current update ends, similar to the pairwise average protocol. For implementation, an index number is assigned for each iteration. Each agent only keeps one-step-further information to guarantee the convergence.

### DETERMINISTIC SCHEDULING

Based on the topology information of a microgrid, deterministic scheduling can improve the efficiency of the multiagent coordination scheme. The performance improvement is based on a better wireless channel utilization by increasing the number of concurrent transmissions [9]. We consider the Metropolis method based weight matrix design. Since the deterministic scheduling problem is equivalent to a clique cover problem which is NP-complete in general, a greedy algorithm can be used to reduce the computational complexity [10]. The algorithm calculates the sequence of the TDMA scheduling by admitting as many wireless transmissions as possible in each time slot. The details of the algorithm are omitted here because of space limitation. Although the deterministic scheduling can provide a near optimal TDMA scheduling, the optimization should be performed whenever an agent is added/removed from the network. Moreover, the network topology should be discovered before the optimization, which is also considered as an overhead. However, as the elements in a microgrid (e.g., DG units and loads) are stationary, the resulting overhead is negligible.

An example of the deterministic scheduling is given in Fig. 2 for a 4-agent case. Each agent can only communicate (and thus interfere) with its direct neighbors. For the unicast communication mode with an ACK message following each data transmission, the collision among ACK messages should also be avoided. Six wireless transmissions are required for each iteration of information update. The optimal scheduling is shown in Fig. 2 which requires four time slots, where each time slot corresponds to the transmission time of a data packet and an ACK message.

Compared with the deterministic scheduling protocol, the update-and-wait/update-and-continue protocol cannot guarantee the optimal link schedule for each iteration since the wireless transmissions are established opportunistically. For a microgrid with a multi-hop wireless net-



**Figure 2.** Deterministic scheduling for the 4-agent case.

work, the request-to-send(RTS)/clear-to-send(CTS) mode should be enabled for the IEEE 802.11 MAC to reduce the contention collisions caused by the hidden terminal problem. As a result, each iteration uses at least six time slots since the RTS/CTS mode suppresses the transmission/reception of all one-hop neighbors of a transmitter-receiver pair, which can introduce the exposed terminal problem [11].

## EXTENSION TO FAULT RECOVERY

In this section, we extend the proposed protocols for the fault recovery in a microgrid. Instead of an information exchange within the entire microgrid as in a wireline network [4], we restrict the information exchange in the disconnected region. The rationale is to reduce the wireless interference caused by unnecessary information exchange in the unfaulted region of the microgrid. In order to discover the excessive generation, the information discovered before the fault should be used. Each agent in the disconnected region sets the initial state value as its net power before the fault, and discovers the total net power in the disconnected region based on the proposed protocols. As each agent in the microgrid either belongs to the disconnected region or the unfaulted region, the excessive generation can be calculated by subtracting the total net power in the disconnected region from the total net power in the microgrid before the fault. Therefore, the local decisions on fault recovery can be made with a lower delay since each agent in the disconnected region discovers the global information faster, which is desirable for a microgrid with highly dynamic and intermittent renewable energy sources.

## A CASE STUDY

In this section, we present a case study of the proposed protocols based on the IEEE 16-bus microgrid test system [4] in a 1200 m × 600 m network region. The simulator is developed based on the ns-2 IEEE 802.11 MAC implementation. The network topology and system configuration are shown in Fig. 3 and Table 1,

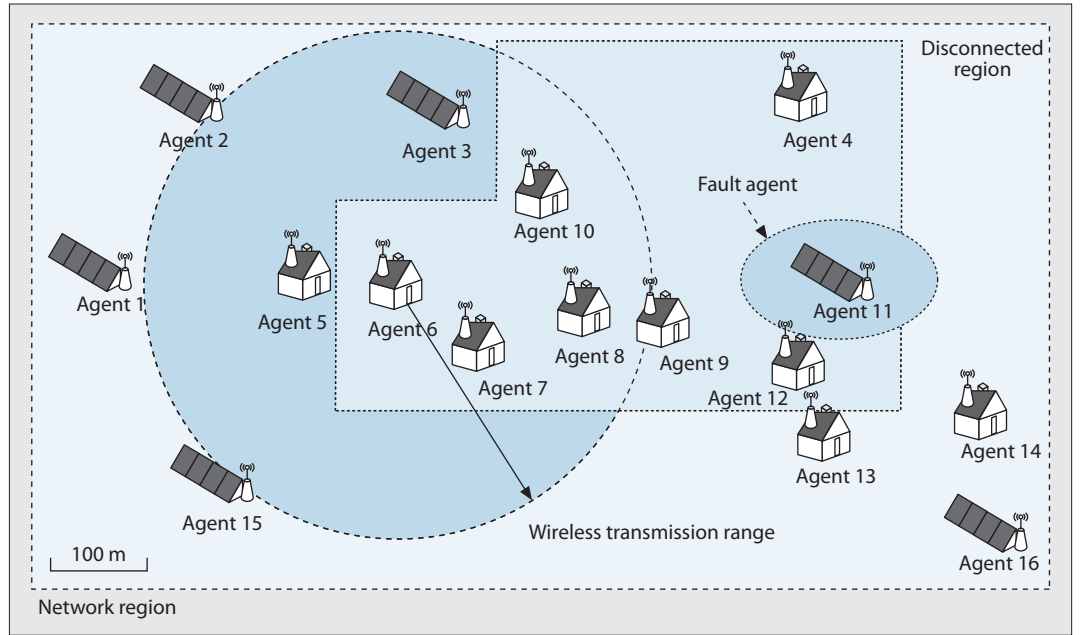
respectively. A fault is considered for the microgrid with respect to a DG unit (i.e., agent 11) as shown in Fig. 3. When the fault occurs, all agents in the disconnected region are automatically isolated by the protection system. As an example, we evaluate the global information discovery processes with respect to the total net power and excessive generation for normal operation and fault recovery, respectively. Since all protocols guarantee the convergence, we denote the average multiagent coordination error at time  $t$  as

$$\sqrt{\frac{1}{|D|} \sum_{m \in D} [x_m(t) - x^*]^2},$$

where  $D$  is the group of agents involved in the global information discovery. For normal operation, we have  $D = A$  and  $x^* = 0$ ; while for fault recovery,  $D$  represents the agents in the disconnected region and  $x^* = -15.6$  MW (or equivalently, an excessive generation of 125 MW in the unfaulted region). For wireless transmission, each data packet contains the state information and performance metric of each agent, and the total net power of the entire microgrid and disconnected region for normal operation and fault recovery, respectively. Each state value is represented by 16 bits [4].

The performance evaluation of normal operation is shown in Fig. 4. The average multiagent coordination error decreases with time for all protocols since the convergence is guaranteed based on the consensus theory. The convergence speed of the update-and-wait protocol is low since the worst-case waiting time is used for each iteration, which is not efficient for the wireless network of a microgrid where the MAC delay (with random access) is highly dynamic. On the other hand, the update-and-continue protocol significantly improves the convergence speed by reducing the waiting time after each update of an agent. The performance of pairwise average protocol is between that of the update-and-wait and update-and-continue protocols. The reason is that, although the MAC delay of the pairwise average protocol is shorter as compared with the worst-case waiting time of the

Based on the topology information of a microgrid, deterministic scheduling can improve the efficiency of the multiagent coordination scheme. The performance improvement is based on a better wireless channel utilization by increasing the number of concurrent transmissions.



**Figure 3.** The network topology based on the IEEE 16-bus test system and the post-fault configuration.

Parameters	Values
Number of agents	16
Net power (MW) of agent 1–16	40 40 50 –25 –35 –20 –15 –25 –5 –30 40 –45 –10 –40 30 50
Fault agent	11
Disconnected agents	4, 6, 7, 8, 9, 10, 11, 12
Wireless transmission range	250 m
Wireless transmission rate	2 Mb/s

**Table 1.** System parameter configuration.

update-and-wait protocol, the information of neighboring agents is not fully exploited, which impairs the convergence speed. Moreover, the decrement of the average multiagent coordination error for the pairwise average protocol is not smooth since each update involves a random pair of agents, which cannot guarantee the intrinsic benefit of the update with respect to the second largest eigenvalue of the product of weight matrices. The deterministic scheduling protocol achieves the best performance since the MAC delay is significantly reduced based on the near optimal sequence of TDMA scheduling.

The performance evaluation of fault recovery is shown in Fig. 5 for the pairwise average and deterministic scheduling protocols. We observe that the global information discovery process converges for both protocols. However, the protocols converge faster by restricting the information exchange in the disconnected region, which significantly reduces the wireless interference caused by the transmission in the unfaulted region.

## CONCLUSIONS AND FUTURE WORK

In this article, we have investigated the multiagent coordination in microgrids via wireless networks. The theoretical foundation with respect to the coordination mechanism, convergence conditions, and convergence speed has been introduced. Several protocols have been proposed for the normal operation and fault recovery, respectively, of a microgrid, which are based on the widely deployed IEEE 802.11 MAC standard. The performance of the proposed protocols has been evaluated by simulations based on the IEEE 16-bus microgrid test system. Numerical results indicate that, our proposed protocols can reduce the multiagent coordination error in comparison with the existing schemes and potentially improve the accuracy of microgrid monitoring and control.

Although multiagent coordination can embrace the advantages of simplicity, provable convergence, and analytically tractable convergence speed, it converges slower in a microgrid via wireless communications because of the interference among concurrent transmissions [8]. A tradeoff between the network performance and deployment cost should be further investigated for the network planning of a microgrid. On the other hand, the efficiency of multiagent coordination in a microgrid via wireless communications can be potentially improved based on a hierarchical/hybrid network architecture. In our future research, we will focus on:

- Hierarchical multiagent coordination: As demonstrated by the recent research [8], long-range wireless communications can possibly improve the convergence speed of multiagent coordination. Therefore, a hierarchical network which aggregates the short-range WiFi/ZigBee devices and long-range cellular (or wireline) devices should be investigated;
- Integration of multiagent coordination and multihop routing: Multiagent coordination

only requires single-hop neighboring information and is simple to implement. However, based on a combination with multihop routing, the information beyond one hop should be exploited to improve the convergence speed.

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## REFERENCES

- [1] S. Chowdhury, S. P. Chowdhury, and P. Crossley, *Microgrids and Active Distribution Networks*, Institution of Engineering and Technology, 2009.
- [2] H. Farhangi, "The Path of the Smart Grid," *IEEE Power Energy Mag.*, vol. 8, no. 1, Jan.-Feb. 2010, pp. 18–28.
- [3] F. Katiraei et al., "Microgrids Management," *IEEE Power Energy Mag.*, vol. 6, no. 3, May-Jun. 2008, pp. 54–65.
- [4] Y. Xu and W. Liu, "Novel Multiagent Based Load Restoration Algorithm for Microgrids," *IEEE Trans. Smart Grid*, vol. 2, no. 1, Mar. 2011, pp. 152–61.
- [5] C. Intanagonwiwat, R. Govindan, and D. Estrin, "Directed Diffusion: A Scalable and Robust Communication Paradigm for Sensor Networks," *Proc. ACM MOBICOM*, Aug. 2000, pp. 56–67.
- [6] V. Blondel et al., "Convergence in Multiagent Coordination, Consensus, and Flocking," *Proc. IEEE CDC-ECC*, Dec. 2005, pp. 2996–3000.
- [7] R. Olfati-Saber, J. Fax, and R. Murray, "Consensus and Cooperation in Networked Multi-Agent Systems," *Proc. IEEE*, vol. 95, Jan. 2007, pp. 215–33.
- [8] S. Vanka, M. Haenggi, and V. Gupta, "Convergence Speed of the Consensus Algorithm with Interference and Sparse Long-Range Connectivity," *IEEE J. Select. Topics Signal Process.*, vol. 5, no. 4, Aug. 2011, pp. 855–65.
- [9] P. Wang and W. Zhuang, "A Collision-Free MAC Scheme for Multimedia Wireless Mesh Backbone," *IEEE Trans. Wireless Commun.*, vol. 8, no. 7, Jul. 2009, pp. 3577–89.
- [10] E. Liu, Q. Zhang, and K. K. Leung, "Clique-Based Utility Maximization in Wireless Mesh Networks," *IEEE Trans. Wireless Commun.*, vol. 10, no. 3, Mar. 2011, pp. 948–57.
- [11] P. Wang, H. Jiang, and W. Zhuang, "A New MAC Scheme Supporting Voice/Data Traffic in Wireless Ad Hoc Networks," *IEEE Trans. Mobile Comp.*, vol. 7, no. 12, Dec. 2008, pp. 1491–503.

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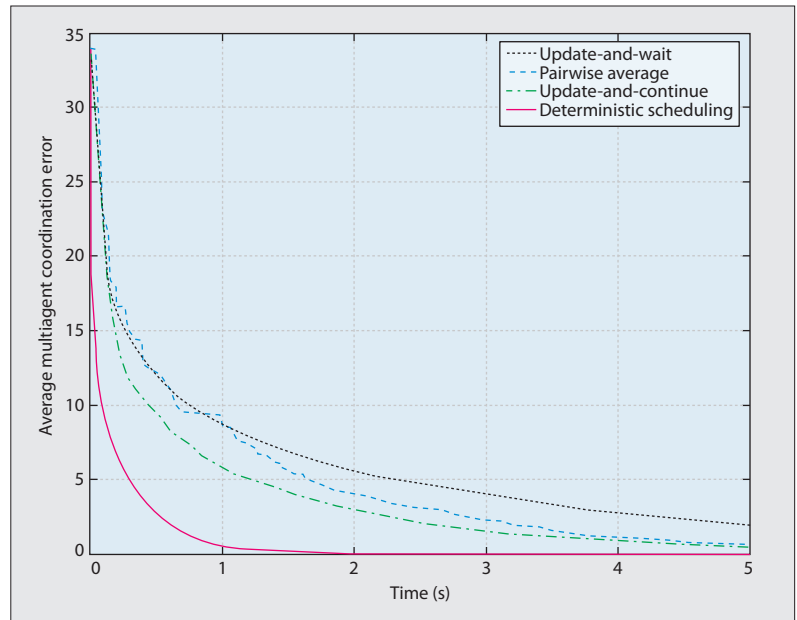


Figure 4. Performance evaluation of normal operation.

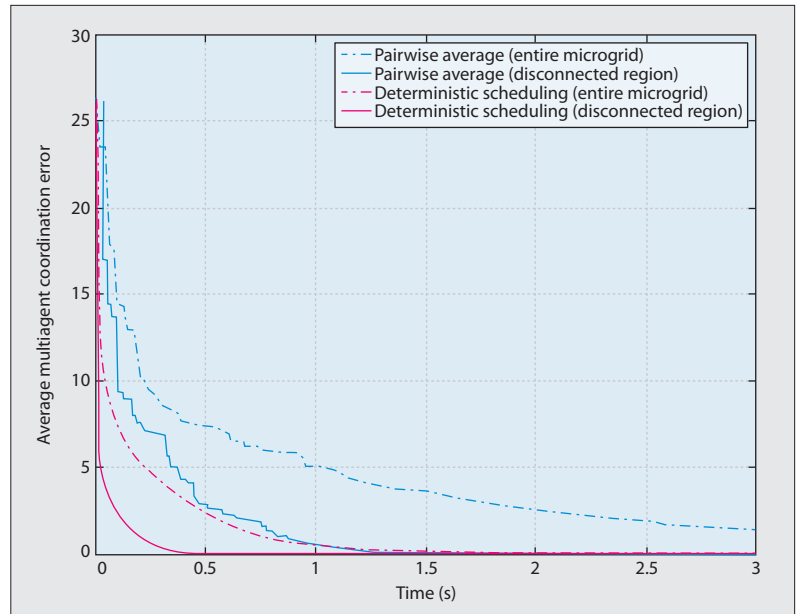


Figure 5. Performance evaluation of fault recovery.

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