A PSO-based Wireless NetworkVirtual Mapping Algorithm in Smart Grid

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***Abstract*—To meet different communication requirements, a smart grid communication framework based on a hybrid network has been widely used. Virtual networks are established for various types of services respectively, and are embedded into heterogeneous substrate networks. Based on the framework, wireless network virtual mapping algorithm based on particle swarm optimization is proposed. In this scheme, the throughput is considered as fitness function, and parameters and operations of the particles are redefined. At last, comparing to basic heuristic algorithms, the proposed algorithm can perform better in term of throughput while satisfying the reliability of real time services.**

Keywords—smart grid; network virtualization; hybrid network; sub-carrier allocation; particle swarm optimization

I. INTRODUCTION

Smart grid is a modern power delivery system, which can monitor, protect and automatically optimize the interconnect components. To control and manage this system, information exchange is an integral part in smart grid. However, because traditional network framework can only be repaired on the basis of existing physical network, it does not really meet present networks of business, data and information diversification[1].Network virtualization can independently operate multiple different virtual networks over a common physical network, and can effectively realize flexible resource allocation and utilization to support real-time and multi-business services. Therefore, an effective network framework with a network virtualization solution is key to smart gird.

To establish an effective network framework with a network virtualization solution that supports real-time and multi-business services in smart gird, we meet the following tow challenges:

1) How to abstract problem model and how to ensure these services to operate independently on different virtual networks.

2) How to efficiently allocate virtual request resources to guarantee the reliability of real-time services and maximize the throughput of best-effort traffic.

To address those challenges, a communications framework based on hybrid network virtualization for smart grid is adopted. Where, the hybrid network consists of wireless mesh network and power line communication (PLC) network. And then we import the object function based on reliability of real-time services to maintain maximize the best-effort traffic throughput. Secondly, a mapping algorithm based on particle swarm optimization (PSO) for a wireless network is proposed to deal with sub-carriers allocation which is an NP-hard problem. At last, the simulation is implemented. Simulation results show that it performs better than a heuristic algorithm proposed in the literature [2].

The rest of this paper is organized as follows: Section II describes related works. In Section III, a communication framework based on hybrid virtualization for smart grid is introduced, and a hybrid network virtualization model is established. Section IV formulates a mapping algorithm based on PSO for a wireless network. Numerical simulation results are presented in Section V and conclusions are drawn in Section VI.

II. RELATED WORK

In recent years, network virtualization for smart gird attracted widespread attentions. Although an optical fiber can provide high capacity and reliability for communication, it is uneconomical and inflexible [3]. Wireless mesh network has an extremely broad application prospects because of its wide coverage, high speed setting up, high bandwidth, low deployment cost. In addition, power line network is added to this framework, constituting a hybrid network.

Virtual network mapping problem is a key technology of network virtualization. There is an extensive literature on virtual network mapping. It includes wired network virtual mapping and wireless network virtual mapping [4]. In the previous research works, there are the priority mapping (e.g. node-priority mapping [5]), collaborative mapping [6], static virtual mapping [7], and dynamic virtual mapping [8]. These methods are all aimed to obtain best virtualization effects in different environments. Although a practical online virtual network mapping algorithm was designed in the literature [6], it will lead to disordered packets and packets loss for physical network need to support division and migration paths. For this problem, virtual mapping problem can be modeled as integer linear programming problem. Because of the inherent computational complexity of virtual mapping problem, intelligent optimization algorithms (such as PSO) are introduced to improve speed and quality of the mapping algorithm [9].

Based on previous research work, for a communications framework based on hybrid network virtualization, we provide a mapping algorithm based on PSO for a wireless network applied in smart gird.Wireless mesh networks is designed to adopt orthogonal frequency division multiple access (OFDMA) technology. Different virtual networks allocate different sub-carriers to be separated, and the enhanced transmission diversity through two physical networks and allocated sub-carriers improves the reliability of real-time services. It can guarantee the reliability of real-time services and maximize the best-effort traffic throughput.

III. Problem Model

A. *Hybrid Network Virtualization*

Network virtualization technology can be used to deploy and verify a next-generation network architecture in different network environments without changing the existing network infrastructure. Hybrid Network virtualization both allows each physical entity to support multiple logical function bodies, and allows multiple physical entities to support the same logical function body. In smart grid, the hybrid network consists of wireless mesh network and PLC network. Since two networks have different topologies and transmission characteristics, the virtual network can be mapped to two heterogeneous physical networks based on various demands.Wireless network virtualization mapping for different virtual requests is illustrated in Fig.1.

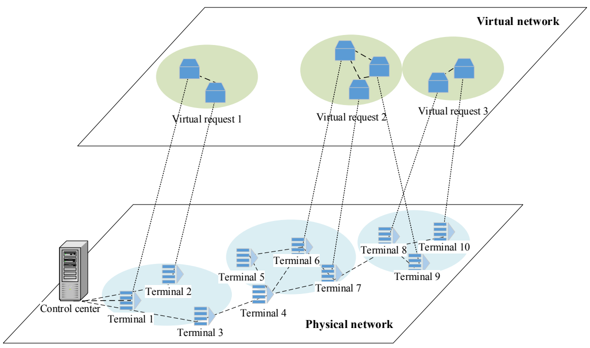

Fig. 1. The wireless network virtualization mapping.

To achieve the purpose of network virtualization, virtual resources must be efficiently mapped onto physical network by relying on advanced network resource mapping algorithm. Virtual network mapping must assign resources instantly in accordance with the virtual network needs, and improve the physical resource utilization as much as possible.

B. *Communication Framework Based on Hybrid Virtualization*

In smart grid, a control center is used to control, monitor, and manage multiple terminals. Each terminal needs to establish a two-way connection to the control center. Information delivery in each area, which is called a service, is abstracted into a virtual network. According to the actual demands, there are the control & operation division and management & data division in smart grid. Owing to the limited capacity of PLC network, it is only fit for the services with small data volume [2]. Consequently, as shown in Fig.2, PLC network is mainly used to establish virtual networks for control and operation services, and they are embedded into the different networks to ensure service diversity in smart grid. In a wireless mesh network, the control & operation division and management & data division can be merged into one virtual network to provide best-effort service.

In a wireless mesh network, OFDMA is used as a communication technology on physical layer, which can make them isolate through allocating irrelevant sub-carrier set for virtual access networks[10]. The transmission bandwidth is divided into a series of non-overlapping orthogonal sub-carriers, and different sub-carriers are allocated to different users to achieve multiple access. Due to different users occupy non-overlapping sub-carrier set, in ideal synchronization, there are no multi-user interference in the system [11]. In addition, the wireless card is half-duplex device. A virtual node must start to work after another virtual node, when two virtual nodes do the sending and receiving operation respectively based on the same physical node. So, it destroys the isolation principle of virtual networks [2]. To solve this problem, wireless mesh network node is equipped with two radio interfaces: an RF interface is specifically for sending (called sending radio), and the other is specially for receiving (i.e. receiving radio).

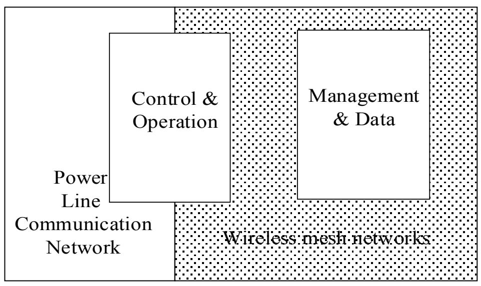

Fig. 2. Some features distribution of the hybrid network.

C. *Virtual Network Mapping Model*

1) *Physical network model*

Use undirected weighted graph $\mathbf{G}_S(\mathbf{N}_S, \mathbf{E}_S)$ as the underlying network model [12, 13]. In this paper, wireless mesh network and PLC network are respectively denoted by $\mathbf{G}_S{}^W(\mathbf{N}_S, \mathbf{E}_S{}^W)$ and $\mathbf{G}_S{}^P(\mathbf{N}_S, \mathbf{E}_S{}^P)$, where, $\mathbf{N}_S$ is the node set (Nodes are fixed in smart grid, so both networks have the same node set), and $|\mathbf{N}_S| = n$ is the number of nodes. The node set $\mathbf{N}_S$ has a control center ($n_S(0)$) and n-1 terminal devices ($n_S(i), i=1,...,n-1$). Each node has two attributes, i.e. the sub-carrier number of sending $S^T(i)$ and the sub-carrier number receiving radios ($S^R(i)$). $\mathbf{E}_S{}^W$ and $\mathbf{E}_S{}^P$ are represented as corresponding networks, where, for $e_W \in \mathbf{E}_S{}^W$, use R_{e_W} as the normalized reliability of wireless link; for $e_P \in \mathbf{E}_S{}^P$, use $R_{e_P} = 1-\varepsilon_P$ (ε_P is PER of PLC network) as the normalized reliability of wireless link.

2) Virtual network requests model

Virtual network requests model, which is similar to the underlying network model, is also denoted by undirected weighted graph $\mathbf{G}_V(\mathbf{N}_V, \mathbf{E}_V)$, where, $\mathbf{N}_V$ is virtual node set, and $\mathbf{E}_V$ is virtual link set [12, 13]. Except for the control center, each virtual terminal node $n_V(i) \in \mathbf{N}_V$ contains three virtual service requests, i.e., a control service request ($\mathbf{c}(i)$),an operation service request ($\mathbf{o}(i)$) request and a best-flow traffic request ($\mathbf{b}(i)$). Each $\mathbf{c}(i)$ and $\mathbf{o}(i)$ contain three attributes: dominated length of the message, its delay request and the reliability request. $\mathbf{c}(i)$ and $\mathbf{o}(i)$ are respectively expressed by two triples $\mathbf{c}(i) = (L_c(i), D_c(i), R_c(i)), \mathbf{o}(i) = (L_o(i), D_o(i), R_o(i))$. In addition, we use $P_c(i)$ and $P_o(i)$ as the actual transmission success probability of $\mathbf{c}(i)$ and $\mathbf{o}(i)$ after being mapped to the heterogeneous physical networks respectively. The best-flow traffic request ($\mathbf{b}(i)$) contains an attribute $\mathbf{f}_b(i)$, expressing the actual satisfied part of the best-effort traffic request after mapping process.

3) Virtual Network Mapping Problem Description

Virtual network mapping is that virtual network requests are mapped into physical network, including node mapping and link mapping. Then, a virtual network mapping under certain constraints can be expressed by g,

$$g : \mathbf{G}_S(\mathbf{N}_S, \mathbf{E}_S) \rightarrow \mathbf{G}'_V(\mathbf{N}_V, \mathbf{E}_V) \tag{1}$$

where $\mathbf{G}'_V \in \mathbf{G}_V$.

Unlike existing virtual network mapping solutions, communication terminals in a smart grid of a service are simply selected according to specified electric devices, so node mapping is deterministic. The communications framework for smart grid proposed in this paper adopts OFDMA technology, so we can allocate sub-carriers according to virtual service requests for each node.

We define a wireless mesh network $\mathbf{G}_S{}^W(\mathbf{N}_S, \mathbf{E}_S{}^W)$ and PLC network $\mathbf{G}_S{}^P(\mathbf{N}_S, \mathbf{E}_S{}^P)$, and three virtual service requests, i.e. a control service request ($\mathbf{c}(i)$), an operation service request ($\mathbf{o}(i)$) request and a best-flow traffic request ($\mathbf{b}(i)$). The sub-carrier assignment matrices for three virtual service requests are found by proposed scheme, and they are expressed by $[s_c(i,j)]_{n\times(n-1)}$, $[s_o(i,j)]_{n\times(n-1)}$ and $[s_b(i,j)]_{n\times(n-1)}$ respectively. The target is to meet requests of real-time service reliability and maximize the business total throughput without violating sub-carrier constraints.

Then, the problem can be formulated as:

$$\max: \sum_{i=1}^{n-1} \mathbf{f}_b(i)$$
$$s.t. \begin{cases} \mathbf{P}_c(i) \geq \mathbf{R}_c(i), \\ \mathbf{P}_o(i) \geq \mathbf{R}_o(i), \\ \mathbf{b}(i) \geq \mathbf{f}_b(i), \\ \sum_{j=1}^{n-1} s_c(i,j) + \sum_{j=1}^{n-1} s_o(i,j) + \sum_{j=1}^{n-1} s_b(i,j) \leq \mathbf{S}(i) \end{cases} \tag{2}$$

This optimization problem shown in equation (2) is a typical NP-hard problem. Traditional mathematical optimization algorithm has a large computational complexity; to some extent, a virtual network mapping algorithm based on genetic algorithm can reduce computational complexity, but it will result in local optimum and it is difficult to find a global optimal mapping algorithm. In order to effectively solve this problem, a virtual wireless network mapping algorithm based on PSO is adopted.

IV. ALGORITHM DESCRIPTION

A. Algorithm theory and relevant concepts redefinition

PSO is a global optimization evolutionary algorithm developed recently, proposed by Kennedy and Eberhart who inspired by the foraging behavior of birds [14].Compared with genetic algorithm, solving rules of PSO algorithm is simpler and with less parameters to be adjusted, so it is widely used in function optimization. Because the existing PSO algorithm cannot solve subcarrier allocation problem in OFDMA system of smart grid directly, we need to redefine the relevant concepts.

Assume that there is M particles in a population, and search them in the D-dimensional space. The position of the *i*-th particle in the *t*-th generation is represented by a D-dimensional vector $\mathbf{X}_i(t) = (x_{t1}, x_{t2}, ..., x_{tD})$, where, flight speed is $\mathbf{V}_i(t) = (v_{i1}, v_{i2}, ..., v_{iD})$, history optimal position of the particle itself is $\mathbf{P}_i(t) = (p_{i1}, p_{i2}, ..., p_{iD})$, and history optimal position of the population is $\mathbf{P}_g(t) = (p_{g1}, p_{g2}, ..., p_{gD})$. The objective function is to seek maximum, for example, mathematical expressions to determine the manner of its best position are as follows:

$$\mathbf{P}_i(t) = \begin{cases} \mathbf{P}_i(t-1), & f(\mathbf{X}_i(t)) \geq f(\mathbf{P}_i(t-1)) \\ \mathbf{X}_i(t), & f(\mathbf{X}_i(t)) \leq f(\mathbf{P}_i(t-1)) \end{cases} \tag{3}$$

$$\mathbf{P}_g(t) = \arg\min\{f(\mathbf{P}_1(t)), f(\mathbf{P}_2(t)), ..., f(\mathbf{P}_M(t))\} \tag{4}$$

where initialization optimum position is $\mathbf{P}_i(0) = \mathbf{X}_i(0)$, and f is fitness function.

Fitness function is used to measure quality standards of particle corresponding solution, and closely related to the objective function of optimization problems. Fitness is determined by the objective function of optimization problem: if the objective function is to solve the maximum value, fitness is greater and more superior solutions is obtained; if objective function is to solve the minimum value, fitness is smaller and the superior solutions is obtained [15].In this paper, the objective function of optimization problem is to maximize business total throughput, i.e.

$$\max \sum_{i=1}^{n-1} \mathbf{f}_b(i) .$$

Therefore, the lager output value of the fitness function is, the better sub-carrier allocation scheme is. Fitness function was deformed by equation (2):

$$f = \alpha(\frac{R_c}{P_c} + \frac{R_o}{P_o} + \frac{f_b}{b}) + \beta(\frac{S_c + S_o + S_b}{S}) \qquad (5)$$

where α, β are restraint coefficients.

In network virtualization of smart grid, the particle is equivalent to the sub-carrier allocation scheme. In this paper, position vector of the particle $\mathbf{X}_i(t) = (x_{t1}, x_{t2}, ..., x_{tD})$ represents the sub-carrier allocation scheme of the *i*-th node in the *t*-th iteration, which is denoted by the sub-carrier allocation mode for three virtual service request in section II, i.e. $[s_c(i,j)]_{n\times(n-1)}$, $[s_o(i,j)]_{n\times(n-1)}$ and $[s_b(i,j)]_{n\times(n-1)}$.In this paper, velocity vector of the particle $\mathbf{V}_i(t) = (v_{i1}, v_{i2}, ..., v_{iD})$ represents sub-carrier allocation mode's adjustment programs of the *i*-th node in the *t*-th iteration, which can be updated as follows:

Velocity:

$$\mathbf{V}_i(t+1) = w \times \mathbf{V}_i(t) + c_1 \times r_1 \times (\mathbf{P}_i(t) - \mathbf{X}_i(t)) + c_2 \times r_2 \times (\mathbf{P}_g(t) - \mathbf{X}_i(t)) \quad (6)$$

Position:

$$\mathbf{X}_i(t+1) = \mathbf{X}_i(t) + \mathbf{V}_i(t+1) \qquad (7)$$

where w is inertia weight; c_1 and c_2 represent acceleration factors of the next position P_i of each particle and the next position P_g respectively; r_1 and r_2 are two separate random numbers($r_1, r_2 \in [0,1]$).

B. Units Virtualization mapping method based on PSO application

In the communication framework of smart grid based on hybrid network virtualization, the hybrid network adopts wireless mesh networks and PLC network (it adopts multi-carrier narrowband communication technology). The implementation of communication framework for smart grid is divided into two major step:

a) Compute transmission success probability of real-time services in PLC network and the reliability requirements of real-time service in wireless mesh network, and allocate sub-carrier for wireless mesh networks to meet reliability requirements.

b) The rest of network resources $\mathbf{G}_S'^W(\mathbf{N}_S, \mathbf{E}_S'^W)$ is obtained from step a), and allocate sub-carriers for wireless mesh network by PSO to achieve the objective of maximizing business total throughput.

The flow chart of the communication framework for smart grid is illustrated in Fig. 3.

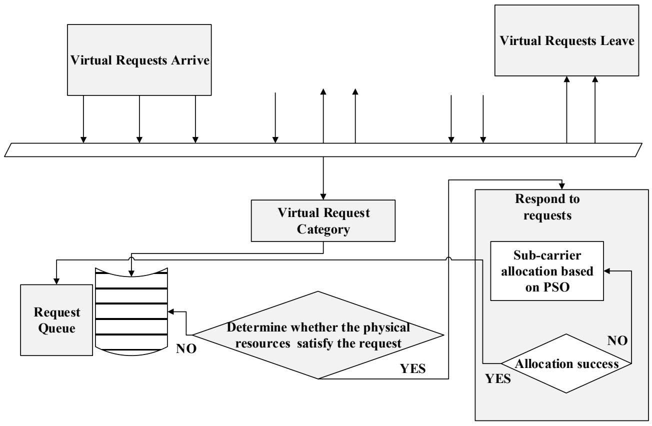

Fig.3. The flow chart of communication framework for smart grid

Implementation steps of subcarrier allocation scheme based on PSO are as follows:

Step1: Initialization parameters, number of particles M in the population, inertia weight w, acceleration coefficients c_1 and c_2 ; setting algorithm termination factor and iteration number.

Step2: Initializing particle swarm, setting the number n of nodes and the number k of sub-carriers to be allocated, randomly generating M subcarriers assigned modes. In order to ensure fairness between each node, the number of sub-carriers assigned to each node is proportional to its data requirements.

Step3: Calculate fitness of sub-carrier allocation program for each particle according to the fitness function.

Step4: Update optimal subcarrier allocation scheme for each particle, as well as globally optimal subcarrier allocation scheme according to fitness, equation(3) and equation(4).

Step5: Update sub-carrier allocation adjustment scheme for each particle and optimal subcarrier allocation scheme according to equation(5) and equation(6).

Step6: Repeat step 3~5, if the number of iterations is reached, stop the iteration, export optimal subcarrier allocation scheme and the largest overall throughput, and the algorithm ends.

V. SIMULATION

To verify effectiveness of network virtualization framework for smart grid based on PSO, simulations are conducted by comparing with a heuristic algorithm proposed in the literature [2]. Experiments mainly study from mapping time, transmission satisfaction of each node and maximum throughput.

A. *Simulation environment*

Simulation scene is set as follows: We generate a node set which contains a control center and 10 terminal nodes. The terminal nodes are numbered from 1 to 10. Each node is equipped with two radios, and each radio has 128 sub-carriers. Simulation parameters are shown in table 1.

TABLE 1. SIMULATION PARAMETERS

Parameter	Value
Number of terminal nodes	10
PLC PER	0.001
Control packet length	1000bits
Control delay request	30 ms
Control reliability request	0.999
Operation packet length	2000 bits
Operation delay request	60 ms
Operation reliability request	0.99
Number of particle	20
Number of iterations	200
Inertia weight	0.6
Acceleration coefficients	0.4,0.6
Constraint factor	0.5,0.5

B. *Result Analysis*

1) *Mapping Time*

The time of 100 successfully mapped simulations is recorded, and an average mapping time of two algorithms are obtained and shown in Table 1. Compared to the heuristic algorithm, PSO requires higher time complexity and resources, because PSO always search global optimal solution within maximum range of iterations.

TABLE 2. AN AVERAGE MAPPING TIME OF TWO ALGORITHMS

Algorithm	PSO	Heuristic Algorithm
Time/s	34.65	22.67

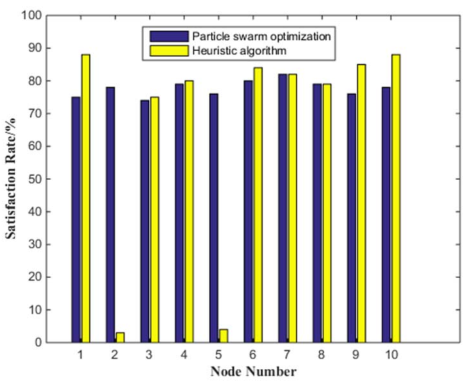

Fig.4. Satisfied rate comparison

2) *Transmission Satisfaction*

We define transmission satisfaction is 12Mbps. We get 10 nodes satisfaction rate using two algorithms to simulate. In Fig. 4, node satisfaction rate of PSO is around 75%, and there is no particular node. Although satisfaction rate of some nodes in heuristic algorithm is over 85%, satisfaction rate of the number 2 and 5 nodes is almost 0%. There are unfair distribution nodes, which led to a serious waste of resources. PSO proposed in this paper considers the fairness of nodes, i.e. sub-carrier allocation is distributed according to the proportion of data requirements. Although at the expense of satisfaction rate of small number of nodes, the waste of resources is reduced.

3) *Maximum Throughput*

The goal of this article is to achieve maximum business throughput, so the reliability requirements and PER in PLC network impacted on this goal are analyzed.

Fig.5 shows that the maximum throughput is obtained by two algorithms in a hybrid network virtualization mapping and a single network virtualization mapping. When a single network virtualization mapping is adopted, the maximize throughput obtained is lower. When there is no PLC network, more sub-carriers in wireless mesh network need to be allocated for real-time services to ensure its reliability. Thus, the remaining sub-carriers are allocated for maximize throughput is few, resulting in a lower maximum throughput obtained finally.

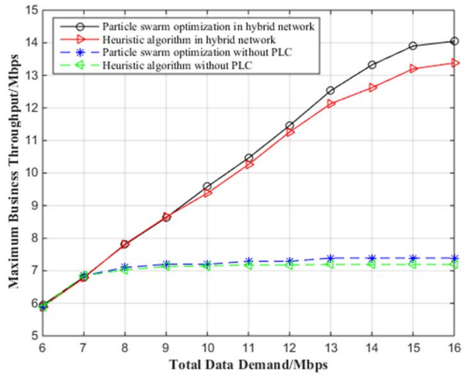

Fig.5. The maximum throughput comparison between hybrid network and a single network

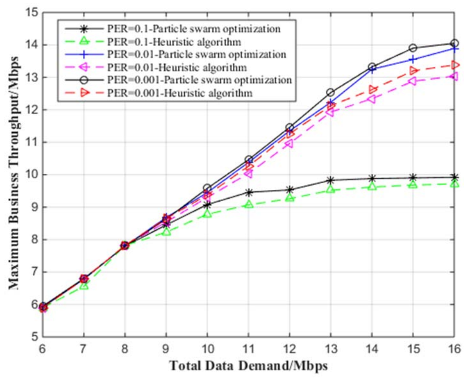

Fig.6. The maximum throughput under different PER in PLC

To further verify the effect of PLC network, as shown in Fig. 6, some cases for two algorithms in hybrid network are tested to obtain the maximum throughput, in which PLC network PER varies. Lower PER implies that PLC network can provide higher transmission reliability, and more sub-carriers in wireless mesh network can be allocated for best-effort traffic. Thus, as is shown in Fig. 6, the smaller PER of PLC network, the greater the maximum throughput are obtained by simulation.

Impact of the real-time services reliability request on the maximum business throughput is shown in Fig. 7. When the reliability request is higher (i.e. R_c varies from 0.999 to 0.99999, R_o varies from 0.99 to 0.9999), the maximum business throughput is lower. Then, when the real-time services reliability request is higher, the more sub-carriers should be allocated for these services. Therefore, the maximum business throughput is negatively related to the reliability request.

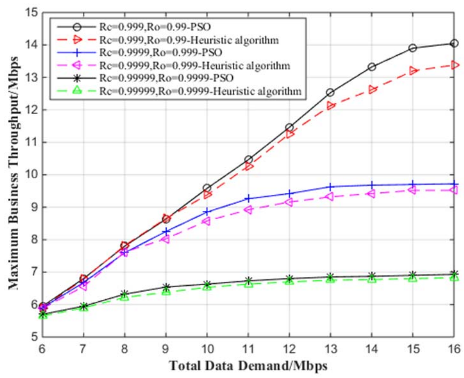

Fig.7. Impact of the reliability request on the maximum business throughput

By observing the mapping case of the two algorithms in the same kind of network, maximum throughput obtained by two algorithms are almost the same at low data requirements service in Fig. 5 , Fig. 6 and Fig. 7. At higher data requirements, the maximum throughput of PSO was always higher than that of heuristic algorithms, and the maximum improvement rate can reach about 6%. Because we always compare the best value and the global optimum individual values at each iteration, and choose the larger total throughput in PSO.

VI. CONCLUSION AND PROSPECT

This article proposed a PSO-based hybrid wireless network virtual mapping algorithm in smart grid. Wireless mesh network and PLC network constitute a hybrid network in this communication framework.PLC network is used to meet more real-time services, thus more sub-carriers are saved for best-effort traffic scheduling in wireless mesh network. Then, the virtual mapping algorithm based on PSO is proposed. Subsequently, a PSO-based hybrid wireless network virtual mapping algorithm is verified to meet real-time service reliability requests and maximize business throughput. Compared with single network, hybrid virtual network mapping algorithm can obtain more maximum throughput. Although the computation time of the algorithm gets a little longer and requires more time complexity and resources, the wireless network mapping based on PSO not only obtain more maximum throughput than the traditional heuristic algorithm, but also prevent unfair node.

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