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Energy-efficient data transmission with proportional rate fairness for NANs of smart grid communication network

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Abstract

In smart grid, the neighborhood area network (NAN) serves as a bridge connecting smart meters and meter data management system (MDMS) and is one of the most important components of the smart grid communication network. In this work, we study the energy-efficient data transmissions from NAN gateways (i.e., routers) to the concentrator that connects the MDMS. Particularly, to assure that each router associated with diverse number of associated smart meters can achieve a required data rate, a set of proportional rate fairness constraints are imposed into the optimization problem. In this case, an optimization problem that balances energy efficiency and fairness is formulated. Due to the fractional form of objective function, the combinatorial constraints on channel allocation variables, and the proportional rate fairness requirements, the formulated energy-efficient data transmission problem is non-convex and extremely computationally complex. In order to solve the problem efficiently, firstly, a subtractive transformation is introduced to handle the objective function, and an iterative algorithm based on Dinkelbach method is proposed; then for the inner loop optimization problem in each iteration, a low-complexity suboptimal algorithm that separates channel allocation and power distribution is developed. Finally, numerical results demonstrate that the proposed algorithm converges in a few steps and achieves a near-optimal energy efficiency performance.

Keywords: Smart grid, Neighborhood area network, WiMAX, Energy-efficiency, Proportional rate fairness

1 Introduction

Smart grid is an automated and widely distributed electricity delivery system with a two-way flow of electricity and information, such that it is capable of monitoring and responding to the changes in everything from power plants to customer preferences to individual appliances [1]. By integrating advanced sensing, communication, and control functionalities in the day-to-day operation of power grid, smart grid has modernized the way the electricity is generated, transported, distributed and consumed, for the purpose of improved efficiency, security, reliability and decreased emissions [2, 3]. However, the key to realizing the aforementioned advantages of smart grid lies in the proper design and implementation of a reliable, secure, and cost-effective smart grid communication network.

Due to the fact that the underlying communication infrastructure of smart grid should support its multitude of monitoring, data collection, and control tasks, the US National Institute of Standards and Technology (NIST) [4] and the IEEE Project 2030 [5] have developed reference architecture models for the smart grid communication network. Generally, in terms of communication coverage and functionality, a smart grid communication network consists of three components, i.e., home area network (HAN), neighbor area network (NAN) and wide area network (WAN). As shown in Fig. 1, the HAN collects sensor and/or smart meter information from a variety of smart devices within home and delivers control information to them for better management of electricity consumption; the NAN is responsible for smart meter communications enabling information exchange between customers and the WAN of utility companies, while the WAN interconnects NANs with the utility companies' private networks. That is to say, the smart grid communication network is an integration of various network segments that maintain the communications among enormous nonhomogeneous devices distributed across broad geographical regions and requiring diverse service of quality [6].

It is widely accepted that providing reliable, secure, robust, scalable and efficient end-to-end information delivery among the HAN, NAN and WAN is crucial for smart grid communication network [7]. For example, a failure in communication network may lead to inaccurate control and severe instability in the power grid. In recent years, the design, optimization and implementation of the smart grid communication network have been a focus for research. Among, [8] discusses the challenges and applications of communication technologies in smart grid and identifies three major challenges, i.e., standards inter-operability, cognitive access and cyber security. Based on a variety of smart grid use cases and selected standards, [9] summarizes the diverse requirements for different applications in HAN, NAN and WAN. It is pointed out that different wired and wireless technologies including powerline communication, WiMAX and long-term evolution (LTE) compete for use in different smart grid communication network domains [10–12], while due to the flexible deployment and environmental adaptiveness without additional cabling cost of wired communication technologies, multiple short- and wide-range wireless communication technologies, such as ZigBee, Bluetooth, Wi-Fi, cognitive radio (CR), WiMAX and LTE, have been applied in the smart grid communication systems [13, 14].

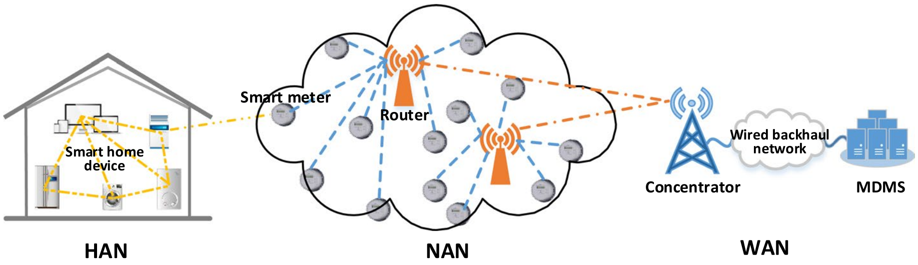

Fig. 1 Smart grid communication network with three representative components

Specifically, the HAN has been widely studied using Zigbee, Bluetooth or Wi-Fi, because of the small coverage and low data rate transmissions [15, 16]. Since the NAN serves as a bridge connecting HAN and WAN and is a critical infrastructure in smart grid to support communications, [17] offers a comprehensive survey to address network topology, gateway deployment, routing algorithms and security issues on the implementation of smart grid NANs. [18] analyzes the potential gains by enabling direct communication using cellular networks. Considering the great potential for large-scale wireless-mesh smart grid NANs, [19] proposes a hybrid multi-channel wireless network combining wireless local area network and wireless mesh network, and [20] presents a systematic approach to generate scale-free topology of wireless-mesh NANs. For uplink transmission and traffic scheduling in smart grid wireless-mesh NANs, [21] presents a multi-gate and single-class back-pressure-based scheduling algorithm, and [22] proposes a Stackelberg game-based power control scheme for hierarchical uplink transmissions. Using IEEE 802.11 s and IEEE 802.16 (mostly known as WiMAX), as well as renewable energy such as solar power, [23] investigates the selection of optimal number of gateways and the geographical deployment methods in NAN design, while for downlink transmission in the typical NAN communication scenario that sends commands from a control center or meter data management system (MDMS) simultaneously to a large number of nodes, [24] proposes a constrained broadcast scheme with minimized latency (CBS-ML) for low-latency NAN communications.

On the other hand, WiMAX has been regarded as a broadband wireless technology that provides support for five service classes for different applications in large cells and can be customized for specific application [25]. Thus, WiMAX technology can well-support point-to-multi-point network and offer inter-operability between different nodes as needed by electric utilities. Owing to its seamless communications, adequate bandwidth, advanced security features, high data rates, wide coverage and scalable networking [26], WiMAX technology is considered as one of the option for smart grid communications. Particularly, [27] reviews the work using WiMAX for data aggregation in smart grid communication network. In order to meet the smart grid communication requirements, [28] investigates the optimized WiMAX profile configuration including the choice of frame duration, type-of-service to traffic mapping, scheduling strategies, and system architecture, and [29] presents a comparative study between LTE and WiMAX technologies applied to the smart grid communication system by simulating a scenario based on IEEE 14-bus transmission test on Network Simulator 3 (NS-3) tool. Besides, in our former work, we provide a heterogeneous NAN that the data collection and transmission are based on different wireless technologies [30]. That is, for the data collection of smart meters with low data rates and short ranges, the underlay and interweave CR-based communication paradigm is suitable, while for the data transmission of routers, since the concentrator is a relatively big radio-wave transmission tower and usually miles away, the routers are equipped with WiMAX operating at unlicensed spectrum.

Different from the existing works on WiMAX-based NANs that emphasize the feasibility analysis [27], physical layer optimization [28], performance comparisons based on simulations [29] and systematic design [30], in this work, we focus on the uplink data transmission in a WiMAX-based NAN to fill the gap on transmission scheduling. Specifically, adopting the heterogeneous NAN architecture proposed in [30], the data transmission phase refers to that multiple wireless routers transmit the data collecting from smart meters associated with them to the concentrator in a longer distance-based WiMAX technology. However, compared to a WiFi-based router, the power consumption of a router with WiMAX is much higher. As a result, considering the limited power supply and high power consumption of routers, energy efficiency is a critical issue for the data transmission of a NAN. Moreover, in addition to the energy efficiency issue, given the fact that the number of smart meters serving by different routers differs widely, we also assure the proportional rate fairness of routers by imposing a set of nonlinear constraints into the optimization problem.

The contributions of this work are summarized as follows:

- Focusing on the data transmission phase of a NAN, and considering a set of nonlinear rate ratio constraints for routers associated with diverse number of smart meters, we formulate an optimization problem that maximizes the energy efficiency performance of the data transmission with the proportional rate fairness among multiple routers.
- Based on the nonlinear fractional programming, we apply a subtractive transformation to handle the objective function. Then, we propose an iterative algorithm based on Dinkelbach method to solve the transformed problem. In each iteration, for the inner loop optimization problem with proportional rate constraints, a low-complexity suboptimal algorithm that separates channel allocation and power distribution is developed.
- Numerical results firstly show the effectiveness of the proposed suboptimal channel and power allocation algorithm for the inner loop optimization problem, including the impact of the proportional rate constraints. Then, the convergence of the iterative algorithm is demonstrated given any initial values of energy efficiency. Finally, it is shown that the performance of the proposed suboptimal algorithm is quite close to the optimal one.

The rest of the paper is organized as follows. We describe the system model in Sect. 2. The problem formulation and the energy-efficient data transmission algorithm with proportional rate fairness is detailed in Sect. 3. Numerical results and discussions for the performance evaluation are given in Sect. 4. Finally, Sect. 5 concludes the paper.

2 System model

2.1 Heterogeneous NAN

As studied in our former work [30], we consider a heterogeneous NAN composed of smart meters, routers and concentrators. The routers are deployed to relay the smart meter data to the concentrator, which connects the MDMS through the WAN. As shown in Fig. 2, the data transmission from smart meters to the concentrator is divided into two phases, i.e., CR-based data collection and WiMAX-based data transmission. Specifically, the low-rate data of multiple smart meters are collected by the corresponding routers based on CR in the first phase, and then the data of a router is transmitted to the concentrator based on high-rate WiMAX in the second phase. Particularly, the WiMAX-based data transmission is deployed in 5.8GHz unlicensed spectrum, which can provide a data rate up to 70Mbps

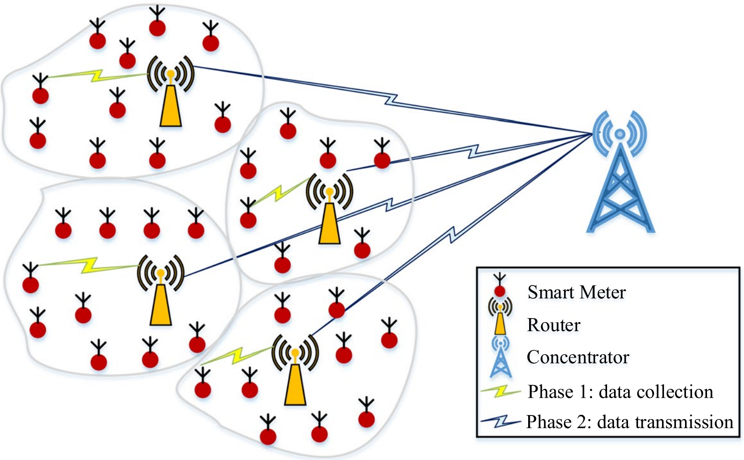

Fig. 2 Heterogeneous NAN

and distance up to 48 Km. In addition, the full-duplex routers can receive and transmit on different frequencies simultaneously.

For clarity, we define the data collection from smart meters to a router as a cluster. Overall, there are a set of $\mathcal{R} = \{1, \ldots, r, \ldots, R\}$ clusters, i.e., routers, in the considered area, and router r collected the data of a set of $\mathcal{S}_r = \{1, \ldots, s, \ldots, S_r\}$ smart meters. Then, considering the sum-rate disparities of smart meters, the routers energy-efficiently transmit the data further to the concentrator with proportional rate fairness. Besides, it is noted that the association between smart meters and routers is assumed to be distance-based and fixed.

2.2 Data transmission model

We consider an OFDM-based WiMAX, where R routers communicate with the concentrator by using a set of channels denoted by $\mathcal{F} = \{1, \ldots, F\}$. Let the channel power gains on channel $f \in \mathcal{F}$ from router r to the concentrator be denoted by $h_{r,d,f}$. All the channels are assumed to be independent flat fading channels, and the white Gaussian noise power on channel f at the concentrator is denoted by $\delta^2_{d,f}$. For simplicity, we assume the perfect channel state information (CSI) on the channel power gains through proper signaling.

Let $b_{r,f}$ be a binary variable that indicates whether channel f is allocated to router r, and $b_{r,f} = 1$ implies channel f is allocated to router r, and vice versa. The constraint of the maximum number of channels of routers is given as

$$\sum_{r \in \mathcal{R}} \sum_{f \in \mathcal{F}} b_{r,f} \leq F. \tag{1}$$

The transmission power of an individual router is also restricted, i.e.,

$$\sum_{f \in \mathcal{F}} b_{r,f} q_{r,f} \leq \overline{Q}_r, \forall r \in \mathcal{R}, \tag{2}$$

where $\overline{Q}_r$ is the prescribed limit for the transmission power of router r.

Lastly, the energy efficiency of the data transmission of NAN is defined as

$$EE = \frac{\sum_{r\in\mathcal{R}} C_r}{\sum_{r\in\mathcal{R}} P_r} \tag{3}$$

where $C_r = \sum_{f\in\mathcal{F}} \frac{\overline{W}}{F} b_{r,f} \log_2(1+\frac{h_{r,d,f}q_{r,f}}{\delta_{d,f}^2})$ and $P_r = q_{r,0} + \eta_r \sum_{f\in\mathcal{F}} b_{r,f}q_{r,f}$ are the rate and the power consumption of router r, respectively, $\overline{W}$ is the overall bandwidth, $q_{r,0}$ and η_r are, respectively, the circuit power consumption and the coefficient of power amplifier of router r.

3 Methods

3.1 Problem formulation

To conserve the energy of routers and take into account the fairness of data transmission of multiple routers, we formulate the problem of channel allocation and power distribution of routers to optimize the energy-efficient data transmission of NAN with proportional rate fairness. Specifically,

$$\begin{aligned} \max_{q_{r,f},b_{r,f}} \ & EE \\ \text{s.t.} \ & \sum_{r\in\mathcal{R}} b_{r,f} = 1, \forall f \in \mathcal{F} \\ & \sum_{r\in\mathcal{R}}\sum_{f\in\mathcal{F}} b_{r,f} \le F \\ & b_{r,f} \in \{0,1\}, \forall r \in \mathcal{R}, f \in \mathcal{F} \\ & C_1 : C_2 : \cdots : C_R = R_1^1 : R_2^1 : \cdots : R_R^1 \\ & \sum_{f\in\mathcal{F}} b_{r,f}q_{r,f} \le \overline{Q}_r, \forall r \in \mathcal{R} \\ & 0 \le q_{r,f} \le q_{r,max}, \forall r \in \mathcal{R}, f \in \mathcal{F} \end{aligned} \tag{4}$$

where R_r^1 is the overall data rate of smart meters served by router r.

It is easily to observe that due to the fractional form of the objective function, the combinatorial constraints on the channel allocation variables and the nonlinear equality constraints of proportional rate fairness, the optimization problem in (4) is non-convex. In the following, we detail the derivation of an efficient joint channel allocation and power distribution algorithm.

3.2 Data transmission optimization

3.2.1 Subtractive transformation

Firstly, a subtractive transformation is introduced to handle the objective function by employing nonlinear fractional programming. Without loss of generality, the maximum energy efficiency ρ^* of the data transmission system is defined as

$$\rho^* = \frac{\sum_{r\in\mathcal{R}} C_r^*}{\sum_{r\in\mathcal{R}} P_r^*} = \max_{b_{r,f},q_{r,f}} \frac{\sum_{r\in\mathcal{R}} C_r}{\sum_{r\in\mathcal{R}} P_r}. \tag{5}$$

Then, the following theorem is presented.

Theorem 1 *The maximum energy efficiency* ρ^* *can be achieved if and only if*

$$\max_{b_{r,f},q_{r,f}} \left\{\sum_{r\in\mathcal{R}} C_r - \rho^* \sum_{r\in\mathcal{R}} P_r\right\} = \sum_{r\in\mathcal{R}} C_r^* - \rho^* \sum_{r\in\mathcal{R}} P_r^* = 0, \tag{6}$$

for $\sum_{r\in\mathcal{R}} C_r \geq 0$ *and* $\sum_{r\in\mathcal{R}} P_r > 0$.

Please refer to the work in [31] for a proof. Theorem 1 shows that for any objective function in fractional form, an equivalent objective function in subtractive form exists, while the "equivalent" means that both problem formulations lead to the same resource allocation policies. In this case, we can focus on finding the optimal joint channel allocation and power distribution policy with the equivalent subtractive objective function in (6). Moreover, the works in [31] and [32] demonstrate the effectiveness of such a transformation.

3.2.2 Iterative algorithm

By adopting the transformed objective function $\sum_{r\in\mathcal{R}} C_r - \rho \sum_{r\in\mathcal{R}} P_r$, we propose an iterative algorithm based on Dinkelbach method to solve the optimization problem in (4). As have been studied in [31] and [32], the Dinkelbach method is a popular technique for solving nonlinear fractional programmings. Specifically, the Dinkelbach method is an iterative algorithm that generates a sequence of ρ values of converging to the maximum energy efficiency ρ^* monotonically, such that $\sum_{r\in\mathcal{R}} C_r^* - \rho^* \sum_{r\in\mathcal{R}} P_r^* = 0$. We summarize the algorithm in Algorithm 1. Given a ρ, once the reformulated problem with an equivalent objective function is globally solved, Algorithm 1 will finally achieve an optimal solution to the optimization problem in (4) according to Theorem 1. That is, the optimal energy efficiency ρ^* and channel and power allocation policy $\{b_{r,f}^*, q_{r,f}^*\}$ can be obtained by iteratively solving the main loop problem in Algorithm 1. In the following, we will show how to solve the inner loop optimization problem with a given ρ in each iteration.

Algorithm 1 Iterative Algorithm for Joint Channel Allocation and Power Distribution in Energy-Efficient Data Transmission for NAN

```
Require: The initial maximum energy efficiency $\rho$, the iteration index $t = 0$, the maximum number of iteration $T_{\max}$, and the maximum toleration $\Delta$
Ensure: The energy-efficient joint channel allocation and power distribution $b_{r,f}^*, q_{r,f}^*, \forall r \in \mathcal{R}, f \in \mathcal{F}$
  repeat
    Solve the inner loop optimization problem for a given $\rho$ and obtain the resource allocation policy $\{b'_{r,f}, q'_{r,f}\}$
    if $\sum_{r\in\mathcal{R}} C'_r - \rho \sum_{r\in\mathcal{R}} P'_r < \Delta$ then
      Convergence=true
      return $\{b_{r,f}^*, q_{r,f}^*\}$ and $\rho^* = \frac{\sum_{r\in\mathcal{R}} C_r}{\sum_{r\in\mathcal{R}} P_r}$
    else
      Set $\rho = \frac{\sum_{r\in\mathcal{R}} C'_r}{\sum_{r\in\mathcal{R}} P'_r}$ and $t = t + 1$
      Convergence=false
    end if
  until Convergence=true or $t = T_{\max}$
```

As shown in Algorithm 1 and optimization formulation in (4), the inner loop optimization problem in each iteration is given as follows:

$$
\begin{aligned}
\max_{q_{r,f},b_{r,f}} & \sum_{r\in\mathcal{R}} C_r - \rho\sum_{r\in\mathcal{R}} P_r \\
\text{s.t.} & \sum_{r\in\mathcal{R}} b_{r,f} = 1, \forall f \in \mathcal{F} \\
& \sum_{r\in\mathcal{R}}\sum_{f\in\mathcal{F}} b_{r,f} \le F \\
& b_{r,f} \in \{0,1\}, \forall r \in \mathcal{R}, f \in \mathcal{F} \\
& C_1 : C_2 : \cdots : C_R = R_1^1 : R_2^1 : \cdots : R_R^1 \\
& \sum_{f\in\mathcal{F}} b_{r,f}q_{r,f} \le \overline{Q}_r, \forall r \in \mathcal{R} \\
& 0 \le q_{r,f} \le q_{r,max}, \forall r \in \mathcal{R}, f \in \mathcal{F}
\end{aligned} \tag{7}
$$

Ideally, to achieve the optimal solution in (7), the channels and power should be allocated jointly. However, this will result in huge computational burden for the concentrator. Furthermore, as the wireless channel frequently changes, the concentrator has to rapidly calculate the optimal channel allocation and power distribution policies accordingly. Consequently, for the delay-sensitive and cost-effective implementations of smart grid communications, low-complexity suboptimal algorithms are desired. Note that to reduce the complexity, separating the channel and power allocation, which decreases the number of variables in the objective function by almost half, is a straightforward way. In the following, section (1) presents a channel allocation scheme, section (2) shows the optimal power distribution given a certain channel allocation, and section (3) discusses the implementations of channel allocation and power distribution.

(1) Suboptimal channel allocation

By assuming the equal power allocation across all the channels, we presents a suboptimal channel allocation algorithm as shown in Algorithm 2. In particular, we define $H_{r,f} = h_{r,d,f}/\delta_{d,f}^2$ as the channel-to-noise ratio for router *r* in channel *f*, and Ω_r is the set of channels assigned to router *r*.

Algorithm 2 Suboptimal Channel Allocation Algorithm in Data Transmission

```
Require: $C_r = 0$, $\Omega_r = \emptyset$, $\forall r \in \mathcal{R}$ and $\mathcal{A} = \{1, \cdots, F\}$
Ensure: $\Omega_r, \forall r \in \mathcal{R}$
  for $r = 1, \cdots, R$ do
    Find $f$ satisfying $h_{r,d,f} \ge h_{r,d,j}$ for all $j \in \mathcal{F}$
    Let $\Omega_r = \Omega_r \cup \{f\}$, $\mathcal{A} = \mathcal{A} - \{f\}$ and update $C_r$
  end for
  while $\mathcal{A} \ne \emptyset$ do
    Find $r$ satisfying $C_r/R_r^1 \le C_i/R_i^1, \forall i \in \mathcal{R}$
    For the found $r$, find $f$ satisfying $h_{r,d,f} \ge h_{r,d,j}, \forall j \in \mathcal{A}$
    For the found $r$ and $f$, let $\Omega_r = \Omega_r \cup \{f\}, \mathcal{A} = \mathcal{A} - \{f\}$ and update $C_r$
  end while
```

The basic idea of the above suboptimal channel allocation algorithm is for each router to use the channel with high channel-to-noise ratio as much as possible. At each iteration, the router with the lowest proportional capacity has the priority to choose which channel to use. Since equal power distribution across all the channels is assumed, the above channel allocation algorithm is suboptimal. Moreover, only coarse proportional rate fairness is achieved after channel allocation. To achieve the goal of maximizing the energy efficiency of data transmission while maintaining accurate proportional rate fairness, the optimal power distribution given channel allocation is required.

(2) Optimal power distribution given channel allocation

For a certain channel allocation, the optimization problem of power distribution is formulated as

$$\begin{aligned} &\max_{q_{r,f}} \sum_{r\in\mathcal{R}} C_r - \rho \sum_{r\in\mathcal{R}} P_r \\ &\text{s.t. } C_1 : C_2 : \cdots : C_R = R_1^1 : R_2^1 : \cdots : R_R^1 \\ &\quad \sum_{f\in\Omega_r} q_{r,f} \le \overline{Q}_r, \forall r \in \mathcal{R} \\ &\quad 0 \le q_{r,f} \le q_{r,max}, \forall r \in \mathcal{R}, f \in \Omega_r \end{aligned} \tag{8}$$

where Ω_r is the set of channels for router r.

The optimization problem in (8) is equivalent to finding the maximum of the following Lagrangian function

$$L = \sum_{r\in\mathcal{R}} (C_r - \rho P_r) - \sum_{r\in\mathcal{R}} \alpha_r \left(\sum_{f\in\Omega_r} q_{r,f} - \overline{Q}_r \right) + \sum_{r=2}^{R} \beta_r \left(C_1 - \frac{R_1^1}{R_r^1} C_r \right), \tag{9}$$

where α_r and $\beta_r, r = \{2, \ldots, R\}$ are the Lagrangian multipliers. By differentiating (9) with respect to $q_{r,f}$ and setting each derivative to 0, we obtain

$$\frac{\partial L}{\partial q_{1,f}} = \frac{\overline{W}}{F} b_{1,f} \frac{h_{1,d,f}}{\delta_{d,f}^2 + h_{1,d,f} q_{1,f}} \frac{1}{\ln 2} - \rho \eta_1 b_{1,f} - \alpha_1 \tag{10}$$

$$\frac{\partial L}{\partial q_{r,f}} = \left(1 - \beta_r \frac{R_1^1}{R_r^1} \right) \frac{\overline{W}}{F} b_{r,f} \frac{h_{r,d,f}}{\delta_{d,f}^2 + h_{r,d,f} q_{r,f}} \frac{1}{\ln 2} - \rho \eta_r b_{r,f} - \alpha_r \tag{11}$$

for $r = 2, \ldots, R$ and $f \in \Omega_r$.

Then, we can easily derive

$$q_{1,f}^* = \frac{\overline{W}}{F} b_{1,f} \frac{1}{\rho \eta_1 b_{1,f} + \alpha_1} - \frac{\delta_{d,f}^2}{h_{1,d,f}} \tag{12}$$

$$q_{r,f}^* = \left(1 - \beta_r \frac{R_1^1}{R_r^1} \right) \frac{\overline{W}}{F} b_{r,f} \frac{1}{\rho \eta_r b_{r,f} + \alpha_r} - \frac{\delta_{d,f}^2}{h_{r,d,f}} \tag{13}$$

for $r = 2, \ldots, R$ and $f \in \Omega_r$.

Furthermore, the Lagrangian multipliers are updated as

$$\alpha_r^{(s+1)} = \left[\alpha_r^{(s)} + \omega_1^{(s)}\left(\sum_{f\in\Omega_r} q_{r,f} - \overline{Q}_r\right)\right]^+, \forall r \in \mathcal{R} \tag{14}$$

$$\beta_r^{(s+1)} = \left[\beta_r^{(s)} + \omega_2^{(s)}\left(C_1 - \frac{R_1^1}{R_r^1}C_r\right)\right]^+, \forall r \in \mathcal{R}, r \geq 2 \tag{15}$$

where ω_i, $i = 1, 2$ are the step sizes of iteration s ($s \in \{1, 2, \ldots, S_{\max}\}$), $S_{\max}$ is the maximum number of iterations and the step sizes should satisfy the condition,

$$\sum_{s=1}^{\infty} \omega_i^{(s)} = \infty, \lim_{s\to\infty} \omega_i^{(s)} = 0, \forall i \in 1, 2 \tag{16}$$

(2) Discussions on channel allocation and power distribution

It is noted that the initial subcarrier assignment is obtained by assuming that all available power $\overline{Q}_r$ is used up, while the actual power consumed to obtain maximum energy efficiency may not be the same with the constrained available power $\overline{Q}_r$, which may result in an inaccurate subcarrier assignment. Then, we update the power and re-execute channel allocation and power distribution iteratively. By introducing such an interaction operation, a better energy efficiency performance is expected to be achieved. However, with numerical simulations, we find that in the most cases, channel allocation and power distribution are executed only once.

4 Results and discussions

4.1 Simulation topology

The simulation topology is shown in Fig. 3, where a square area is further divided into four subregions (clusters). A router is located at the center of each subregion, and the concentrator is some distance (xc) away from the center on the horizontal axis.

4.2 Performance evaluation

Firstly, we show the performance of the proposed suboptimal algorithm for the inner loop optimization problem. Given $xc = 800$ m and four routers as shown in Fig. 3, we present the weighted sum rate (the objective function of the inner loop optimization problem, i.e., $\sum_{r\in\mathcal{R}} C_r - \rho \sum_{r\in\mathcal{R}} P_r$) versus the number of channels F in Fig. 4. It is shown that the proposed suboptimal algorithm performs slightly inferior to the optimal scheme, but it is more robust to the increase in the number of channels, since it allocate the channels greedily. Also, with the increase in the number of channels, the weighted sum rate of two schemes decrease slowly, because of that the quickly increased power consumption overweigh the growing sum rate. Besides, it is easy to find that within certain limits, larger maximum transmission power of routers on each channel brings higher weighted sum rate.

Then, we demonstrate the convergence and effectiveness of the iterative algorithm for joint channel allocation and power distribution in energy-efficient data transmission.

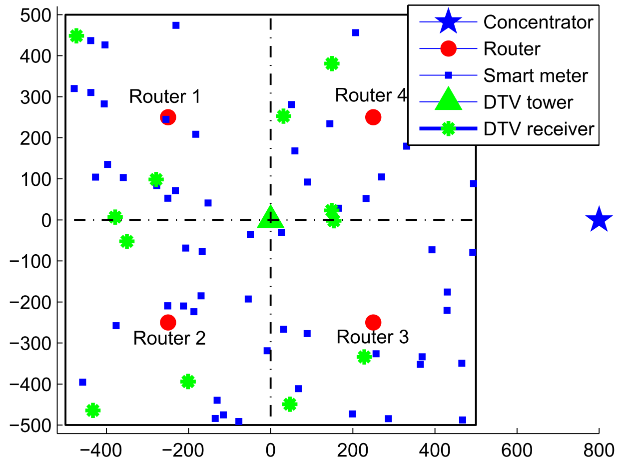

Fig. 3 Simulation topology

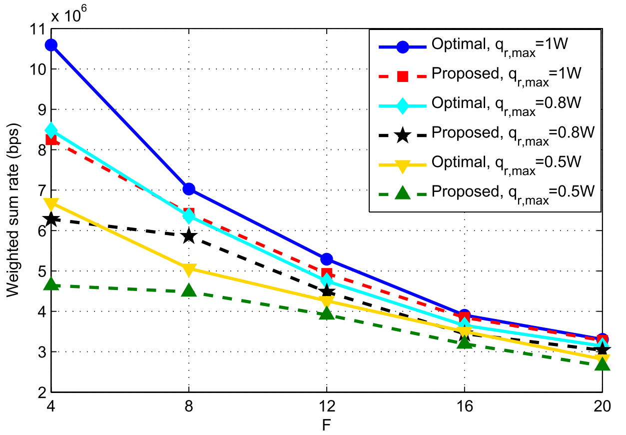

Fig. 4 Performance comparison of optimal and proposed algorithms for inner loop versus the number of channels

Figures 5, 6, and 7, respectively, show the sum rate, sum power and energy efficiency ρ of the respective optimal and proposed algorithms. Particularly, the optimal algorithm means adopting optimal channel allocation and power distribution for the inner loop optimization problem. From Figs. 5, 6, and 7, we can easily see that the iterative algorithm can converge in only a few steps, and the initial ρ, i.e., ρ_0 in the figures, does not affect the results of the iterative algorithm. Moreover, it is shown that for the overall energy-efficient data transmission with proportional rate fairness, the performance of the proposed algorithm is quite close to the optimal one.

5 Conclusions

In this work, we study the energy-efficient data transmission with proportional rate fairness for a NAN in the smart grid communication network. Specifically, the proportional rate fairness refers to the facts that the rate constraints can be configured at the concentrator, hence, rate allocation of routers with diverse number of associated smart meters is flexible. In this case, the proposed optimization problem maximizes the

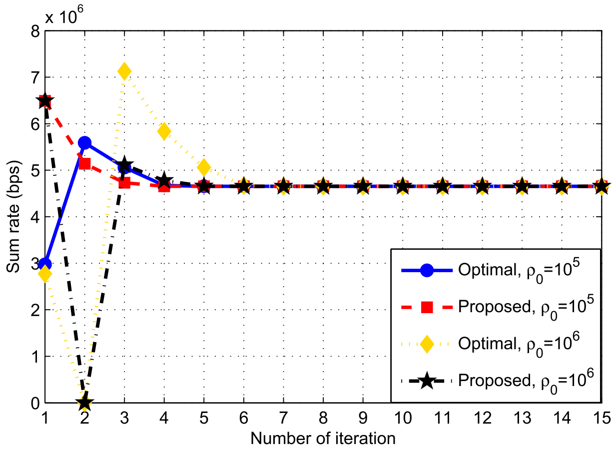

Fig. 5 Sum rate of optimal and proposed algorithms for data transmission versus number of iteration

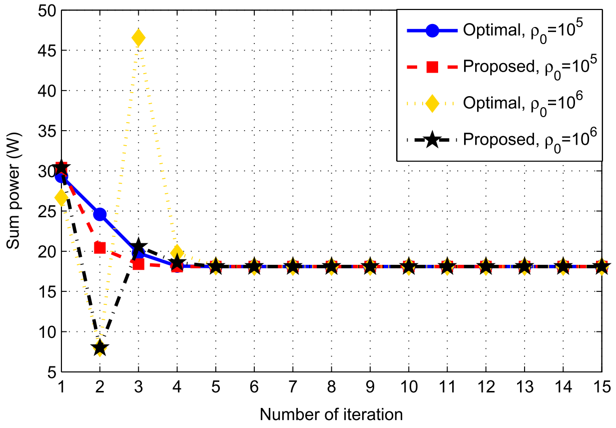

Fig. 6 Sum power of optimal and proposed algorithms for data transmission versus number of iteration

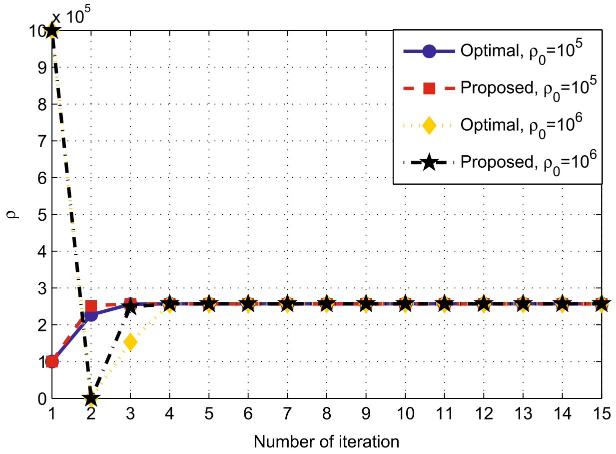

Fig. 7 Energy efficiency of optimal and proposed algorithms for data transmission versus number of iteration

energy efficiency while maintaining proportional rate fairness among routers. To solve the formulated optimization problem, firstly, via nonlinear fractional programming, a transformation is introduced to handle the objective function and an iterative algorithm based on Dinkelbach method is proposed; then, a low-complexity suboptimal algorithm, where channel allocation and power distribution are carried out separately, is developed to solve the inner loop optimization problem in each iteration with a given energy efficiency value. Numerical results firstly show that the proposed suboptimal channel allocation and power distribution algorithm can achieve above 95% of the optimal performance in a 4-router 16-channel system and is more robust to the increase in the number of channels. It is then demonstrated that the proposed iterative algorithm for energy efficiency maximization with proportional rate fairness converges in a few steps and achieves quite-close performance compared with the optimal one.

Abbreviations

NAN	Neighborhood area network
MDMS	Meter data management system
NIST	National Institute of Standards and Technology
HAN	Home area network
WAN	Wide area network
LTE	Long-term evolution
CR	Cognitive radio
NS-3	Network Simulator 3
CSI	Channel state information

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Author contributions
XW and QH developed the idea for the study and did most of the theoretical and numerical analyses, and YY and HM refined the ideas and carried out additional analyses. All authors discussed the results and approved the final manuscript.

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Availability of data and materials
The authors state the data available in this manuscript.

Declarations

Ethics approval and consent to participate
This work does not involve human participants, human data or human tissue.

Consent for publication
This work does not contain any individual person’s data in any form.

Competing interests
The authors declare that they have no competing interests.

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