Energy Efficiency Cooperative Scheme for Cluster-based Capillary Networks in Internet of Things Systems

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***Abstract*—Cooperative multiple-input-single-output (CMISO) scheme has been proposed to prolong the lifetime of cluster heads (CHs) in cluster-based IoT systems. However, the CMISO scheme introduces additional energy overhead to cooperative nodes (Coops) and further reduce the lifetime of these devices. In this paper, we first formulate the problem of cooperative coalition selection for CMISO scheme to prolong the average battery operating time among the whole network, and then propose to apply the quantum-inspired particle swarm optimization (QPSO) to select the optimum cooperative coalition. Simulation results proved that the QPSO algorithm outperforms particle swarm optimization (PSO) and quantum genetic algorithm (QGA).**

***Index Terms*—capillary networks, cluster, cooperative MISO communication, energy efficiency, network lifetime, QPSO.**

I. Introduction

Internet of Things (IoT) systems are viewed to have potential to improve the operational efficiency of many industrial applications. The capillary networks were introduced to improve reliable and energy efficient communications for the IoT systems. The capillary networks are specific local networks which consist of a group of wireless devices to be connected to the other communication infrastructure such as mobile networks [1]. It uses clustering mechanism to improve energy efficiency [2]. Clustering mechanism organizes devices into different clusters and selects cluster heads (CHs) which consequently transmit the aggregated data to the sink device via communication infrastructure networks. However, the CHs consume more energy compared to other devices in the networks, as they take more responsibility and dissipate additional energy in long-haul transmission which is the most energy consuming phase of the communication between the cluster and the sink device. Cooperative multiple-input-single-output (CMISO) scheme was then proposed to solve the aforementioned problem [3]. CMISO introduces additional cooperative nodes (Coops) to help CH in long-haul transmission.

In [4], authors applied nonlinear programming method to deploy an optimal number of Coops in order to balance the energy consumption among all devices in wireless sensor networks (WSNs). In [5], the authors focus on the cluster lifetime in multi-hop WSNs with CMISO scheme. In particular, the authors investigate the cluster lifetime by changing the transmission schemes, the sizes and transmission distances of clusters. In [6], authors focused on analysing the system performance in terms of overall packet error rate and energy consumption in cluster-based wireless networks using cooperative multi-input-multi-output (CMIMO) technique. However, how to select the optimum Coops in a specific scenario is not considered in [4] - [6]. Furthermore, in terms of energy efficiency, most literature considers the minimization of overall energy consumption, instead of prolonging network lifetime which reflects not only the energy consumption of the network but also the fairness of energy consumption distribution among individual devices.

The aforementioned challenges raise the concerns of the optimum cooperative coalition selection in cluster-based capillary networks to prolong network lifetime. Evolutionary algorithm is believed to have potential in solving such coalition selection problem. Quantum-inspired particle swarm optimization (QPSO) combines the advantages of the quantum computing theory and the evolutionary algorithm. Compared with particle swarm optimization (PSO), QPSO adopts novel rotation angle and quantum bit techniques so it has the characteristics of strong searching capability, rapid convergence, short-computing time, and small-population size [7].

In this paper, we introduce a battery model to evaluate the network lifetime by battery operating time and then propose to select the cooperative coalition by QPSO. Extensive simulations have been conducted to evaluate the performance of QPSO algorithm compared with another two evolutionary algorithms, PSO and quantum genetic algorithm (QGA).

The rest of this paper is organized as follows. Section II introduces the system model, the power consumption model, and the problem formulation. In Section III, we explain the QPSO algorithm in detail and propose the use of QPSO algorithm to obtain the optimum cooperative coalition with the objective of maximizing the average battery operating time of all devices. Simulation results are provided in Section IV, and conclusions are drawn in Section V.

II. System Model and Problem Formulation

A. System Model

The system model considers a cluster in a typical energy-limited capillary networks for IoT systems with $\mathcal{N}_{total}$ devices: one CH, CMs with the number of $\mathcal{N}_{CM}$ and Coops with the number of $\mathcal{N}_{Coop}$ as shown in Fig.1, where $\mathcal{N}_{total} =$

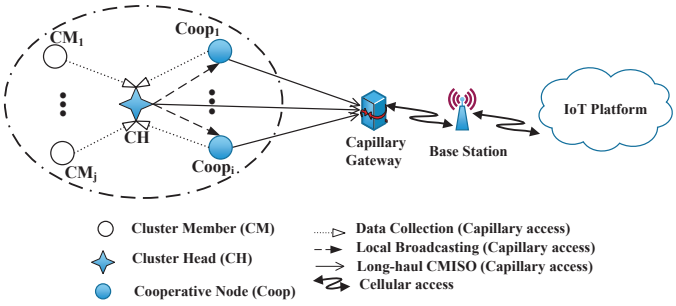

Fig. 1. System model

$1 + \mathcal{N}_{CM} + \mathcal{N}_{Coop}$. In this paper, we assume the additive white Gaussian noise (AWGN) channel with squared power path loss for intra-cluster communications within the cluster, as well as the frequency-nonselective and slow Rayleigh fading for the long-haul transmission between the cluster and the capillary gateway. In addition, considering the fact that the communication environment is more complex in the long-haul transmission, we assume the long-haul transmission with respect to the wavelength gives rise to independent fading coefficients. In developing the strategy, M-ary quadrature amplitude modulation (MQAM) is adopted.

The communication protocol consists of the following three phases:

- Data collection phase (DC): CH collects and aggregates data from all CMs and Coops.
- Local broadcasting phase (LB): CH broadcasts the aggregated data to all Coops.
- Long-haul cooperative transmission phase (LH): CH and Coops jointly encode and transmit the aggregated data to the capillary gateway based on orthogonal space-time block codes (STBC). Then the data information is further forwarded to the IoT platform through capillary gateway and the base station.

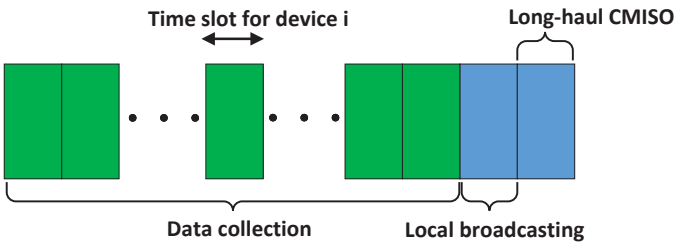

Fig. 2. TDMA time slots of three phases

In addition, TDMA scheduling is adopted in the above communication protocol, as shown in Fig. 2. Denote the duration of one time slot to be t_ω, the active time of CH, $Coop(i)$ where $i \in 1, \cdots \mathcal{N}_{Coop}$ and $CM(j)$ where $j \in 1, \cdots \mathcal{N}_{CM}$ are as follows,

$$\begin{aligned} t_{CH} &= (\mathcal{N}_{total} - 1)t_\omega + t_\omega + t_\omega = (\mathcal{N}_{total} + 1)t_\omega, \\ t_{Coop}(i) &= t_\omega + t_\omega + t_\omega = 3t_\omega, \\ t_{CM}(j) &= t_\omega + 0 + 0 = t_\omega. \end{aligned} \tag{1}$$

B. Battery Model

The battery model in [8] is used in this work. When a battery is discharge at current rate I_c in time period $[t_s, t_e]$, the available capacity $C_{avl}(I_c, T, t_s, t_e, \beta^2)$ can be expressed as follows,

$$C_{avl}(I_c, T_{op}, t_s, t_e, \beta^2) = C_{init} - I_c F(T_{op}, t_s, t_e, \beta^2), \tag{2}$$

where

$$\begin{aligned} F(T_{op}, t_s, t_e, \beta^2) &= (t_e - t_s) \\ &+ 2\sum_{k=1}^{\infty} \frac{e^{-\beta^2 k^2 (T_{op} - t_e)} - e^{-\beta^2 k^2 (T_{op} - t_s)}}{\beta^2 k^2}, \end{aligned} \tag{3}$$

C_{init} is the initial battery capacity, β^2 is a constant related to the diffusion rate of the battery, which can be determined by data fitting [9], and T_{op} is the total operating time of battery.

C. Power Consumption Model

In this paper, we use the power consumption model as defined in [10]. The total power consumption along the single path can be divided into two main components: power consumption and all power amplifiers P_{PA} and power consumption of all other circuit blocks P_c. As in [10], the power consumption of power amplifiers is linearly dependant on the transmit power P_t. Then the power consumption per link can be expressed as

$$P = P_{PA} + P_c = (1 + \alpha)P_t + P_c, \tag{4}$$

where $\alpha = \xi/\eta - 1$ with η being the drain efficiency [11] of the RF power amplifier, and ξ being the peak-to-average ratio (PAR), which is dependent on the modulation scheme and the associated constellation size. As referred to [10], $\xi = 3(M - 2\sqrt{M} + 1)/(M - 1)$ in MQAM coded communication. P_c is composed of the transmitter circuit blocks power consumption denoted by P_{ct} and the receiver circuit blocks power consumption denoted by P_{cr}.

In the MQAM-based connection, the transmit power P_t in (4) can be calculated according to the link budget relationship as follows,

$$P_t = \frac{(4\pi)^2 M_l N_r}{G_t G_r \lambda^2} \cdot \frac{\bar{E}_b}{N_0} R_b d^\kappa, \tag{5}$$

where d is the distance between transmitter and receiver, κ is the channel path loss exponent, G_t and G_r are the transmitter and receiver antenna gains respectively, M_l is the link margin which indicates the difference between the receiver sensitivity and the actual received power, N_r is the single-sided power spectral density of the receiver noise, λ is the carrier wavelength, $\bar{E}_b/N_0$ is the normalized average energy per bit required for a given BER specification to the noise spectral density, R_b is the system bit rate.

As referred to [12], the average $\bar{E}_b/N_0$ of the intra-cluster communication with a square constellation MQAM in AWGN channel is given by

$$\frac{\bar{E}_b}{N_0}\Big|_{intra} \doteq \frac{M-1}{3\log_2 M}\left[Q^{-1}\left(\frac{\bar{P}_{BER}^{intra}\log_2 M}{4(1-1/\sqrt{M})}\right)\right]^2, \tag{6}$$

where $Q(x)=\int_x^\infty \frac{1}{2\pi}e^{-\frac{u^2}{2}}du$ and $\bar{P}_{BER}^{intra}$ is the average BER of intra-cluster communication.

In [13], the the average $\bar{E}_b/N_0$ of the inter-cluster communication with a square constellation MQAM in Rayleigh fading channel is given by

$$\begin{aligned}\frac{\bar{E}_b}{N_0}\Big|_{inter} &\doteq (N_{coop}+1)\frac{2(M-1)}{3\log_2 M}\\ &\cdot\left[\frac{1}{4}\left(\frac{4(1-1/\sqrt{M})\binom{2(N_{Coop}+1)-1}{N_{Coop}+1}}{\bar{P}_{BER}^{inter}\log_2 M}\right)^{\frac{1}{N_{Coop}+1}}-1\right],\end{aligned} \tag{7}$$

where $\bar{P}_{BER}^{inter}$ is the average BER of inter-cluster communication.

D. Power Consumption of CH, Coops and CMs

In the data collection phase, the CH acts as the receiver dissipating the receiving path power consumption while all CMs and Coops transmit data to the CH, dissipating the transmitting path power consumption. As the assumption of squared power path loss in intra-cluster communication, the power consumption per bit of CH, $Coop(i)$ where $i\in 1,\cdots\mathcal{N}_{Coop}$ and $CM(j)$ where $j\in 1,\cdots\mathcal{N}_{CM}$, can be expressed as,

$$\begin{aligned}&P_{CH}^{DC}=P_{cr},\\ &P_{Coop}^{DC}(i)=\frac{(4\pi)^2M_lN_r}{G_tG_r\lambda^2}R_bd_{i,CH}^2\cdot\frac{\bar{E}_b}{N_0}\Big|_{intra}+P_{ct},\\ &P_{CM}^{DC}(j)=\frac{(4\pi)^2M_lN_r}{G_tG_r\lambda^2}R_bd_{j,CH}^2\cdot\frac{\bar{E}_b}{N_0}\Big|_{intra}+P_{ct},\end{aligned} \tag{8}$$

where $d_{i,CH}$ is the distance between Coop i and CH, and $d_{j,CH}$ is the distance between CM j and CH.

In the local broadcasting phase, CH acts as transmitter to broadcast the aggregated data to Coops, dissipating the transmitting path power consumption, and all Coops receive data information from the CH, dissipating the receiving path power consumption. Due to the broadcast nature of the wireless channel, if the Coop with the maximum distance from CH denoted by d_{max} can receive the data from the CH, the other Coops can simultaneously receive these data. Then the power consumption per bit of CH, $Coop(i)$ where $i\in 1,\cdots\mathcal{N}_{Coop}$ and $CM(j)$ where $j\in 1,\cdots\mathcal{N}_{CM}$, can be expressed as,

$$\begin{aligned}&P_{CH}^{LB}=\frac{(4\pi)^2M_lN_r}{G_tG_r\lambda^2}R_bd_{max}^2\cdot\frac{\bar{E}_b}{N_0}\Big|_{intra}+P_{ct},\\ &P_{Coop}^{LB}(i)=P_{cr},\\ &P_{CM}^{LB}(j)=0.\end{aligned} \tag{9}$$

In the long-haul transmission phase, CH and Coops jointly transmit the aggregated data to the capillary gateway, dissipating the transmitting path power consumption. Thus, the power consumption per bit of CH, $Coop(i)$ where $i\in 1,\cdots\mathcal{N}_{Coop}$ and $CM(j)$ where $j\in 1,\cdots\mathcal{N}_{CM}$, can be expressed as,

$$\begin{aligned}&P_{CH}^{LH}=\frac{(4\pi)^2M_lN_r}{G_tG_r\lambda^2}R_bd_{g,CH}^{\kappa_{g,CH}}\cdot\frac{\bar{E}_b}{N_0}\Big|_{inter}+P_{ct},\\ &P_{Coop}^{LH}(i)=\frac{(4\pi)^2M_lN_r}{G_tG_r\lambda^2}R_bd_{i,g}^{\kappa_{i,g}}\cdot\frac{\bar{E}_b}{N_0}\Big|_{inter}+P_{ct},\\ &P_{CM}^{LH}(j)=0,\end{aligned} \tag{10}$$

where $d_{g,CH}$ and $d_{i,g}$ are the distance between CH/Coops i and capillary gateway respectively, $\kappa_{g,CH}$ and $\kappa_{i,g}$ are the path loss exponent between CH/Coops i and capillary gateway in the range between 2 and 3.

E. Packet Size for Data Aggregation and Orthogonal STBC

Assume all devices transmit data packet of the same size, denoted by L. The packet size after data aggregation in [14] is

$$L_{agg}=\frac{\mathcal{N}_{total}}{\mathcal{N}_{total}\varphi_{agg}-\varphi_{agg}+1}L, \tag{11}$$

where φ_{agg} is the aggregation factor.

In the long-haul transmission, all Coops together with the CH encode and transmit the transmission sequence based on the aggregated data packet according to orthogonal STBC. As referred to [15], training overhead is introduced by the CMISO scheme for channel estimation. Therefore, the packet size in the long-haul transmission is,

$$L_c=\frac{F_{block}}{F_{block}-\rho_{train}(N_{Coop}+1)}L_{agg}, \tag{12}$$

where F_{block} is the block size of STBC code and $\rho_{train}(N_{Coop}+1)$ is the number of training symbol.

F. Problem Formulation

In [16], the average current required to power a device during period $[t_s,t_e]$ can be obtained by,

$$\bar{I}_c=\frac{P_{total}}{\phi V}, \tag{13}$$

where P_{total} is the overall power consumption of period $[t_s,t_e]$, ϕ and V denote the DC-DC converter output efficiency and voltage respectively.

The battery operating time can then be expressed as,

$$\begin{aligned}T_{op}&=\frac{C_{avl}(I_c,T_{op},t_s,t_e,\beta^2)}{\bar{I}_c}\\ &=\frac{C_{init}\phi V}{P_{total}}-(t_e-t_s)-2\sum_{k=1}^{\infty}\frac{e^{-\beta^2k^2(T_{op}-t_e)}-e^{-\beta^2k^2(T_{op}-t_s)}}{\beta^2k^2}.\end{aligned} \tag{14}$$

Thus, denote the initializing time to be t_0, the battery operating time of CH, $Coop(i)$ where $i\in 1,\cdots\mathcal{N}_{Coop}$ and $CM(j)$ where $j\in 1,\cdots\mathcal{N}_{CM}$, can be expressed as,

$$\begin{aligned}T_{CH}^{op}&=\frac{C_{init}(CH)\phi V}{LP_{CH}^{DC}+L_{agg}P_{CH}^{LB}+L_cP_{CH}^{LH}}-(t_{CH}-t_0)\\ &-2\sum_{k=1}^{\infty}\frac{e^{-\beta^2k^2(T_{CH}^{op}-t_{CH})}-e^{-\beta^2k^2(T_{CH}^{op}-t_0)}}{\beta^2k^2},\end{aligned} \tag{15}$$

$$T_{Coop}^{op}(i) = \frac{C_{init}(i)\phi V}{LP_{Coop}^{DC}(i) + L_{agg}P_{Coop}^{LB}(i) + L_c P_{Coop}^{LH}(i)} - (t_{Coop}(i) - t_0) - 2\sum_{k=1}^{\infty} \frac{e^{-\beta^2 k^2 (T_{Coop}^{op}(i) - t_{Coop}(i))} - e^{-\beta^2 k^2 (T_{Coop}^{op}(i) - t_0)}}{\beta^2 k^2}, \tag{16}$$

$$T_{CM}^{op}(j) = \frac{C_{init}(j)\phi V}{LP_{CM}^{DC}(j)} - (t_{CM}(j) - t_0) - 2\sum_{k=1}^{\infty} \frac{e^{-\beta^2 k^2 (T_{CM}^{op}(j) - t_{CM}(j))} - e^{-\beta^2 k^2 (T_{CM}^{op}(j) - t_0)}}{\beta^2 k^2}. \tag{17}$$

The research problem is to find the optimum cooperative coalition $\mathcal{C} = \{CH, Coop_1, \cdots, Coop_{\mathcal{N}_{Coop}}\}$ in order to maximize the average battery operating time $\bar{T}_{op}^{avg}$ under given BER threshold $\bar{P}_{BER}^{THR}$. Then the research problem in this work is expressed as,

$$\underset{\mathcal{C}}{\text{maximize}}\, \bar{T}_{avg}^{op} = \frac{\sum_{k=1}^{\mathcal{N}_{total}} T^{op}(k)}{\mathcal{N}_{total}}$$
$$s.t. \quad \begin{cases} 0 \le \mathcal{N}_{Coop} \le \mathcal{N}_{total} - 1 \\ \bar{P}_{BER}^{intra} \le \bar{P}_{BER}^{THR} \\ \bar{P}_{BER}^{inter} \le \bar{P}_{BER}^{THR} \end{cases}. \tag{18}$$

III. Description and Analysis of Algorithm

PSO is an evolutionary computing technique based on the bird flocking principle. In PSO, a swarm consists of several particles and each particle represents a candidate solution to the optimization problem. QPSO uses quantum coding mechanism to encode each particle. QPSO was tested on some benchmark functions and experimental results showed that QPSO outperforms PSO [17].

A. Quantum Particle Swarm Optimization

Qubit-based QPSO encodes each particle by a quantum bit (qubit). A qubit is defined as a pair of composite numbers (α, β), where $|\alpha|^2 + |\beta|^2 = 1$ and $\alpha > 0$, $\beta > 0$. Then the quantum velocity of particle m at generation t is defined as

$$\mathbf{v}_m^t = \begin{bmatrix} \alpha_{m1}^t & \alpha_{m2}^t & \cdots & \alpha_{m\mathcal{R}}^t \\ \beta_{m1}^t & \beta_{m2}^t & \cdots & \beta_{m\mathcal{R}}^t \end{bmatrix}, \tag{19}$$

where $m \in [1, 2, \cdots, h]$, h is the number of particles and $\mathcal{R} = \mathcal{N}_{total} - 1$ which represents number of Coops candidates in this work. Since $\beta_{mn} = \sqrt{1 - \alpha_{mn}^2}$, we can simplify (19) as

$$\mathbf{v}_m^t = [\ \alpha_{m1}^t \quad \alpha_{m2}^t \quad \cdots \quad \alpha_{mR}^t\ ]. \tag{20}$$

The quantum particle position according to (20) can be expressed as

$$x_{mn}^t = \begin{cases} 1 & \text{if} \quad \delta_{mn} > (v_{mn}^t)^2 \\ 0 & \text{if} \quad \delta_{mn} \le (v_{mn}^t)^2 \end{cases}, \tag{21}$$

where $\delta_{mn} \in [0, 1]$ is uniform random number. In this paper, the quantum position indicates whether the device n in particle m is a member of the cooperative coalition: $x_{mn}^t = 1$ represents that device n in particle m is a Coop at generation t; otherwise, device n in particle m is a CM at generation t.

Denote the fitness value of particle m at generation t to be f_m^t , then the local individual optimum fitness value (the best fitness value of particle m) $\mathbf{f}_m$ and the corresponding local individual optimum position $\mathbf{p}_m$ is defined as below,

$$f_m^{pbest} = \max\{f_m^1, f_m^2, \cdots, f_m^t\}, \tag{22}$$
$$\mathbf{p}_m = \mathbf{x}_m^{pbest}. \tag{23}$$

Similarly, the global optimum fitness value (the best fitness value of all particles) $\mathbf{f}_g$ and the corresponding global optimum position $\mathbf{p}_g$ is defined as below,

$$f_{gbest} = \max\{f_1^{pbest}, \cdots, f_m^{pbest}, \cdots, f_h^{pbest}\}, \tag{24}$$
$$\mathbf{p}_g = \mathbf{p}_{gbest}. \tag{25}$$

At generation $t + 1$, the quantum rotation angle θ_{mn}^{t+1} is updated by

$$\theta_{mn}^{t+1} = k_1(p_{mn} - x_{mn}^t) + k_2(p_{gn} - x_{mn}^t), \tag{26}$$

where k_1 and k_2 are two positive learning factors of cognitive and social acceleration, respectively.

The updated velocity of the quantum particle m at $t + 1$ generation is

$$v_{mn}^{t+1} = \begin{cases} \sqrt{1 - (v_{mn}^t)^2}, & \text{if } \theta_{mn}^{t+1} = 0 \text{ and } \delta = c_1 \\ \left| v_{mn}^t \cos\theta_{mn}^{t+1} - \sqrt{1 - (v_{mn}^t)^2} \sin\theta_{mn}^{t+1} \right|, & \text{otherwise} \end{cases} \tag{27}$$

where δ is a uniform random number between 0 and 1, and c_1 is a constant which refers to the mutation probability, $c_1 \in [0, 1/\mathcal{R}]$.

B. QPSO-based Cooperative Coalition Selection

The cooperative coalition selection process based on QPSO is executed by the capillary gateway. In the network initialization, each device reports its individual information (i.e. residual energy and location) to the capillary gateway. QPSO-based cooperative coalition selection is summarized in Algorithm 1. Denote the maximum generation to be T_{max}.

IV. Simulation Results

Assume 25 devices are randomly distributed located within a square with $100m$ side length. All devices are powered by two AAA Li-FeS2 battery [18], which has has 1.5-volt nominal voltage and 1200mAh nominal capacity. The capillary gateway is located at the top corner of the scenario if not otherwise specified in the following simulation. To compare with the peer work, we also simulate PSO [19] and QGA [20] as reference. The scenario setting and all algorithms are implemented via MATLAB. The system parameters are given in Table I.

First, one of the main difficulties of applying an evolutionary algorithm to a given problem is to decide an appropriate set of parameter values. In order to find the optimum particle number

Algorithm 1 Qubit-QPSO to select Cooperative Coalition

for $i = 1, \cdots, \mathcal{N}_{total}$ **do**
  Assume device i to be CH for this iteration.
  Initialize quantum position of particle m $\mathbf{x}_m^1$ where $m \in [1, 2, \cdots, h]$.
  Compute the fitness value of quantum particle m by (18) where $m \in [1, 2, \cdots, h]$.
  Update $\mathbf{p}_m^1$ and $\mathbf{p}_g^1$ correspondingly from (22) to (24).
  for $t = 1, \cdots, T_{max} - 1$ **do**
    for $m = 1, \cdots, h$ **do**
      Update θ_m^{t+1}, $\mathbf{v}_m^{t+1}$ and $\mathbf{x}_{mn}^t$ of quantum particle m by (26), (27) and (21) respectively.
      Compute the fitness value f_m^{t+1} by (18).
      Update f_m^{pbest}, $\mathbf{p}_m$, f_g and $\mathbf{p}_g$ correspondingly from (22) to (24).
    end for
  end for
  The optimum fitness value of device i as the CH is $f_g(i) = f_g^{T_{max}-1}$ and the corresponding $\mathbf{p}_g(i) = \mathbf{p}_g^{T_{max}-1}$ is the optimum cooperative coalition for device i.
end for
The optimum fitness value is expressed as $f_{final} = \max\{f_{g1}, \cdots f_{gi}, \cdots f_{g\mathcal{N}_{total}}\}$ and the corresponding $\mathbf{p}_{final}$ is the best cooperative coalition.

TABLE I
SYSTEM PARAMETERS

$M_l = 40dB$	$N_f = 10dB$	$N_r = -161dBm/Hz$
$R_b = 10kbps$	$G_T G_R = 5dBi$	$\lambda = 0.12m$
$t_\omega = 0.1s$	$\eta = 0.47$	$L = 100bit$
$M = 16$	$\beta = 0.35$	$F_{block} = 200$
$\rho_{train} = 2$	$\varphi_{agg} = 0.5$	$t_0 = 0s$
$k_1 = 0.06$	$k_2 = 0.03$	

and generation number for the assumed scenario, we compare the fitness value of different number of particles for QPSO algorithm in Fig. 3. It can be seen that with the number of generation growing, all curves converge to a similar fitness value. In addition, with the increase of particle number, the curve converges to the optimum fitness value quicker. This is because more particles means better opportunity to find the optimum fitness value, however, introducing more particles also contributes to higher time complexity. Therefore, we set the particle number to be 10 and generation number to be 80 in the following simulation.

Next, Fig. 4 and Fig. 5 take the location of capillary gateway into consideration. We set $\bar{P}_{BER}^{THR}$ to be 10^{-5}. The x axis in Fig. 4 and Fig. 5 is the long-haul distance between the capillary gateway and the top corner of the scenario. It is observed that the QPSO outperforms PSO and QGA in terms of average battery operating time by approximately 10% in Fig. 4. Moreover, the location of capillary gateway is closely related to the long-haul distance, which indicates that the energy consumption in long-haul communication dominates

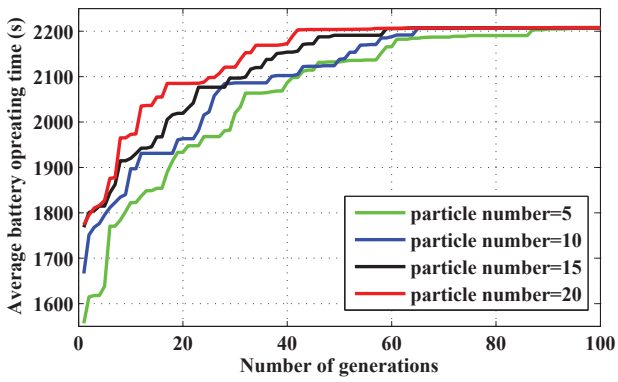

Fig. 3. Number of generation vs. fitness value

the average battery operating time. Fig. 5 investigates the number of Coops with different location of capillary gateway. In general, more Coops can be selected in order to prolong the average battery operating time with the increase of long-haul distance. Note that although the selected Coops by QPSO can contribute to better average battery operating time, the number of Coops selected by QPSO is not the highest, which indicates that higher number of Coops is not necessary. In addition, as for QPSO, the number of Coops remains the same from $150m$ to $250m$, because additional suitable Coops cannot be found.

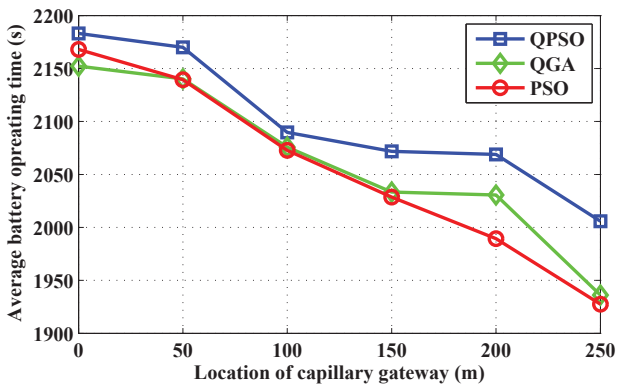

Fig. 4. Location of capillary gateway vs. average battery operating time

Finally, Fig. 6 and Fig. 7 illustrate the average battery operating time and number of Coops in terms of BER threshold $\bar{P}_{BER}^{THR}$, respectively. The capillary gateway is located at the top corner of the scenario. Due to optimum cooperative coalition selected by QPSO, QPSO outperforms QGA by approximately 8% and PSO by approximately 12% considering average battery operating time in Fig. 6. Correspondingly, the number of Coops selected by QPSO is also not highest, as shown in Fig. 7. Besides, we can also conclude that more Coops can be selected in long-haul transmission in order to guarantee better QoS requirement.

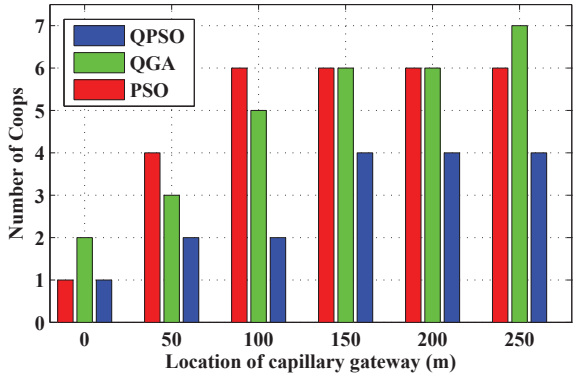

Fig. 5. Location of capillary gateway vs. number of Coops

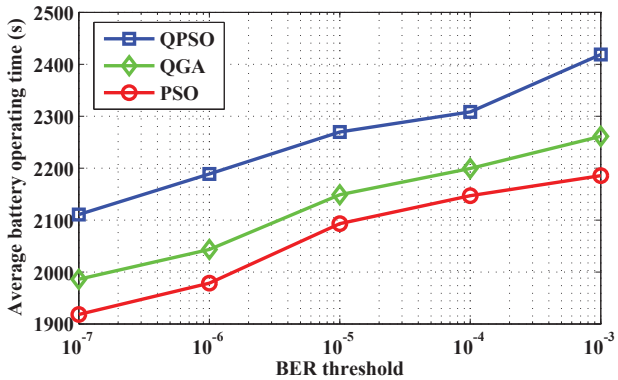

Fig. 6. BER threshold vs. average battery operating time

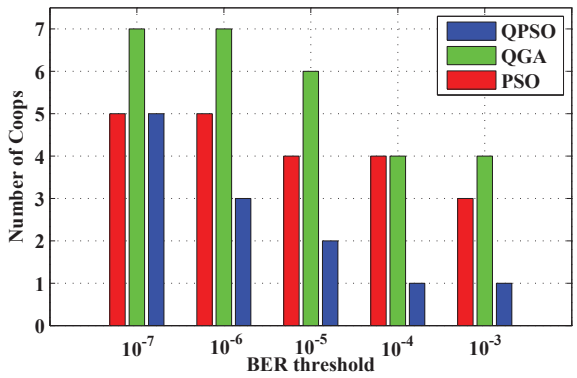

Fig. 7. BER threshold vs. number of Coops

V. Conclusions

In this paper, we investigate the CH and Coops cooperative coalition selection using QPSO algorithms with the aim of maximizing the average battery operating time in cluster-based IoT systems. We show that both the CH and Coops selection plays an important role in data forwarding. QPSO algorithm is applied in order to select optimum Coops for pre-selected CH. Simulation results show that the proposed QPSO algorithm outperforms PSO and QGA in terms of average battery operating time.

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