A Spectrum Efficient Self-Admission Framework for Coexisting IEEE 802.15.4 Networks under Heterogeneous Traffics

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Abstract. *Due to the limited bandwidth resource and the interference among networks, it is challengeable to coordinate the bandwidth resource of multiple IEEE 802.15.4-based wireless personal area networks (WPANs) with heterogeneous traffics, especially in a distributed mode. In this paper, to handle this problem, we first propose a renewal carrier sense multiple access (CSMA)-based self-admission access mechanism for coexisting WPANs in order to maximize the frequency resource utilization and satisfy the diverse rate requirements of heterogeneous traffics. Secondly, we propose the time-space-hard core point process (TS-HCPP) to abstract the renewal CSMA-based self-admission access process for the IEEE 802.15.4 network with multi-channels. TS-HCPP considers the correlation of time and space, and appropriately judges the strong interference between coexisting WPANs, which can solve the density underestimation problems of traditional HCPP. Finally, relying on the TS-HCPP, we obtain the optimum combination of access parameters, which meets the minimum service rate requirements for heterogeneous traffics and maximizes the frequency resource utilization. The simulation results show that the density of coexisting WPANs evaluated by the TS-HCPP matches the experimental results, and an improvement in spectral efficiency of coexisting WPANs can be achieved in our proposed self-admission framework.*

Keywords

Coexisting IEEE 802.15.4 network, time-space-hard core point process (TS-HCPP), spectral efficiency, renewal carrier sense multiple access (CSMA)-based self-admission process

1. Introduction

Many IEEE 802.15.4-based [1] networks, which communicate over the 2.4 GHz industrial, scientific, and medical (ISM) band, have been developed recently [2–4]. The IEEE 802.15.4-based wireless personal area networks (WPANs) are affected by interference from other WPANs over the crowed ISM band due to their limited power capabilities, which limits their coexistence capacities and drastically degrades their performance [5], [6]. Thus, a vacant channel is very precious and must be utilized carefully. In a coexistence scenario, where many WPANs coexist in the same vicinity, if the active periods of different WPANs overlap, the transmissions interfere with each other and thus cause transmission errors. Some scholars devoted to solving the issue. In [7], [8], the authors proposed a distributed coexistence method for IEEE 802.15.4-based networks operating in the beacon-enabled mode. In this method, each network coordinator learned about the surrounding environment, and scheduled its superframe properly to minimize the mutual interference. However, the incoming WPAN sensed the channel for a time equal to the largest beacon interval, and obtained the time offset for each beacon, which cannot meet the requirement of low power consumption of IEEE 802.15.4 standard. And the collision probability in CSMA process was high, which reduced the system throughout. In [9–11], to optimize network performance, the authors used the hard core point process (HCPP) to model the coexisting IEEE 802.15.4-based networks. However, the HCPP underestimated the density of coexisting WPANs for the reason that it did not consider the correlation of time and space, and there existed the problem of the strong interference misjudgment between coexisting WPANs. That caused a waste of bandwidth resources and also resulted in the coarse evaluation of the network performance, such as transmission capacity. Hence, it is challengeable to design a spectrum efficient access mechanism and propose a method to model the coexisting network, which are suitable for the coexisting WPANs.

In this paper, we focus on the scenario where heterogeneous beacon-enabled star-connected networks (SCNs) coexist in the multi-channel environment. The concept of heterogeneous in this paper refers to that the SCNs have different average service rates for carrying diverse traffics. Each SCN consists of a coordinator node (CN) and a number of terminal nodes (TNs). Each CN and its attached TNs follow a superframe structure for their communications. The superframe structure is divided into three parts: the

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beacon, the active period and inactive period. The communications of the CN and TNs in the same SCN become active during the active period of a superframe.

We develop a renewal CSMA-based self-admission framework to improve spectral efficiency of coexisting IEEE 802.15.4-based networks under heterogeneous traffics in the multi-channel environment. The proposed framework includes three parts: the renewal CSMA-based self-admission access mechanism for maximizing the time and frequency domain utilization, the time-space-HCPP (TS-HCPP) to abstract the renewal CSMA-based self-admission access process of coexisting IEEE 802.15.4-based networks in the multi-channel environment, and the optimization of the combination of access parameters (i.e., the expectation of back-off value) to meet the service rate requirements of heterogeneous traffics.

The major contributions of the work can be summarized as follows:

- We propose a renewal CSMA-based self-admission access mechanism. Compared to the traditional CSMA, the advantage of the renewal CSMA-based access is that each network possesses one unique access parameter (i.e., the expectation of back-off value) that we need to calculate. That is beneficial for optimizing network performance. The access mechanism improves spectral efficiency of coexisting IEEE 802.15.4-based networks in the multi-channel environment, such that more networks can coexist in the crowded ISM band.
- We propose the TS-HCPP to abstract the renewal CSMA-based self-admission process of WPANs in the multi-channel environment. Considering the correlation of time and space, as well as the collisions in access process of CNs, TS-HCPP can appropriately judge the strong interference between CNs. To the best of our knowledge, it is the first time to investigate collisions in the HCPP-type model. The simulation results show that the TS-HCPP is superior to traditional HCPP in terms of evaluating the coexisting network performance.
- For heterogeneous traffics, the optimum combination of access parameters is obtained by the enumeration method in the case of limited number of WPANs. That can meet the different communication requirements of WPANs and maximize the frequency resource utilization at the same time. We validate the spectrum efficiency of the renewal CSMA-based self-admission access framework by simulation.

The rest of the paper is organized as follows. In Sec. 2, the related works are reviewed. In Sec. 3, we present the network model and channel model. In Sec. 4, we propose the renewal CSMA-based self-admission access mechanism and present coexistence analysis for multi-channel scenario in TS-HCPP. In Sec. 5, the numerical and simulation results are presented. We conclude the paper in Sec. 6.

2. Related Work

The CSMA mechanism is widely employed in distributed wireless networks due to its simplicity and performance efficiency [12]. HCPP is a powerful tool for modeling CSMA networks. In [13], the authors used the Matérn HCPP to model a random CSMA wireless network under general fading environments, and captured the density of simultaneously active transmitters. However, the Matérn HCPP underestimates the density for the reason that it does not consider the correlation of time and space of the nodes. The authors of [14] presented a modified Matérn HCPP which mitigates the density underestimation problem of the traditional Matérn HCPP via considering not only the point with the lowest mark but also the point with the second lowest mark. The proposed HCPP model in [14] is only effective when the density of parent Poisson point process (PPP) is not particularly high. In [15], the author proposed a modified Matérn HCPP called TM-HCPP to model dense IEEE 802.11 networks for all values of initial node density and exclusion radius, which retained more concurrence transmission nodes than traditional Matérn HCPP. However, the above work only focused on the simultaneously active transmitters with the same access behavior in a random wireless CSMA network.

In the past three years, some scholars began to use HCPP to model coexisting CSMA networks based on IEEE 802.15.4 standard and perform analysis and optimization. In [9], the fundamental tradeoff between energy efficiency and area spectral efficiency of wireless body area networks (WBAN) was first investigated under the Poisson point process (PPP) model and HCPP model. In addition, the optimum density of WBANs coexistence is obtained in one frequency channel. In [10], using a HCPP type II model, the authors proposed a joint carrier-sensing threshold and power control strategy to meet the demand of coexisting WBANs based on the IEEE 802.15.4 standard, which improves the overall system throughput and reduces interference in one frequency channel. In [11], the authors used HCPP to develop a novel framework to design spectrum-efficient multi-channel random wireless networks based on the IEEE 802.15.4 standard. The proposed framework maximizes both spatial and time domain utilization under channel gain uncertainties. These works pay more attention to the coexisting networks with the same access behavior. However, the Matérn HCPP is a conservative model; it underestimates the density of simultaneous transmitting nodes in a certain degree when the density of network becomes high. And the problem becomes severe in multi-channel wireless communication scenarios. The coarse estimation on the density of simultaneous transmitting nodes results in unfaithful performance evaluations of coexisting IEEE 802.15.4 networks, such as the outage probability and transmission capacity. Also, in [11] the authors did not consider the collisions in CSMA process and the different service rate requirements under heterogeneous traffics, which are also important problems of modeling coexisting network.

3. System Model

3.1 Network Model

In this paper, the network model consists of multiple stationary SCNs that are distributed in the R^2 Euclidean space. Figure 1 is a typical scene of our focused communication scenarios, the SCNs with different data transmission rates are colored differently. For saving energy, the communications between the CN and TNs in the same SCN become active during the active period in a superframe, and go to the sleep mode during the inactive period.

We adopt a Poisson bipolar model, where the distance between the transmitter and the receiver is R, to model the spatial distribution of CNs and TNs [16–18]. Hence, we denote an SCN by its CN. Let $\psi = \{x_i: i = 1,2,3,\dots\}$ be the point process modeling the spatial locations of the CNs, where x_i indicates the location of the i^{th} CN in the R^2 Euclidean space. It is assumed that the locations of all CNs are independent. To simplify the analysis, we assume that there always exists one active link in each SCN during its active period (i.e., saturation conditions are assumed).

The probability of n CNs included in the $CS(\subset R^2)$ is given by $P_{\text{cs}} = (\lambda A)^n \exp(-\lambda A) / n!$ where CS is the carrier sensing range of the CN. Since the point process is used to model the CNs, hereafter, we use the notations "a point in the point process" and "a CN in the network" interchangeably in the following sections.

3.2 Channel Model

We consider a power-law path loss model, where the signal power decays at the rate $Kr^{-\eta}$ with the distance r, where K denotes the propagation constant, and η is the path-loss exponent. Also, Rayleigh fading environment is considered. The channel (power) gain from a transmitter $a \in R^2$ to the receiver $b \in R^2$ is denoted by $h(a,b)$, which corresponds to exponential distribution, $h(x,y) \sim \exp(\mu)$ with mean $1/\mu$. All the channel gains are assumed to be independent from each other.

A signal can successfully be decoded if its signal-to-interference-plus-noise-ratio (SINR) is larger than a certain threshold β. Otherwise, the intended receiver experiences signal interruption.

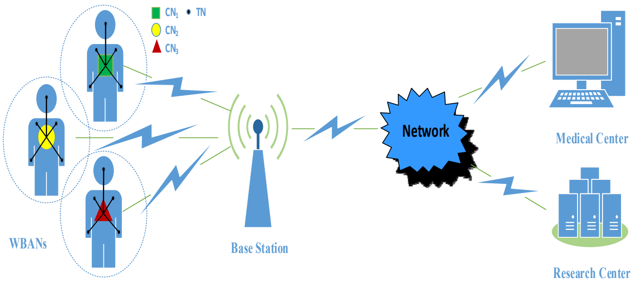

Fig. 1. A scenario of WBANs coexistence.

4. Self-Admission Framework for Co-existing IEEE 802.15.4 Networks

In this section, first, we develop a renewal CSMA-based self-admission access mechanism. Then, we propose the TS-HCPP to abstract the renewal CSMA-based self-admission access process for the coexisting IEEE 802.15.4-based networks in the multi-channel environment. Finally, we obtain the optimum combination of access parameters, which can meet the diverse communication requirements of WPANs and maximize the frequency resource utilization simultaneously.

4.1 Renewal CSMA-Based Self-Admission Access Mechanism

According to the IEEE 802.15.4, the CN is responsible to find the channel to schedule the superframe for its SCN's operation. When a SCN is activated, the CN scans the available frequency channels in a sequential order until it finds a channel to schedule its superframe. However, the protocol in the CSMA period cannot maximize the frequency resource utilization and satisfy the diverse rate requirements of heterogeneous traffics when the access behaviors of all the CNs are same.

Inspired by a renewal process [19], [20], we propose a renewal CSMA-based self-admission access scheme, the procedure of which is shown in Algorithm 1. At each frequency channel, the CN accesses the channel following the self-admission protocol so that its active period does not overlap with the active period of any other SCN within its contending domain.

Algorithm 1 The Renewal CSMA-based Self-Admission Access Protocol

```
1: Initialization;
2: Time variable $t_i$← '0';
3: Waiting for the start of the next superframe;
4: Sense the channel;
5: if there exists an idle channel
6:   generate the value of the back-off counter $m_i \sim p(u_i)$;
7:   sense the channel again when $m_i$ is reduced to zero;
8:   if there exists an idle channel
9:     send data for an active duration;
10:    return to step 2;
11:  else
12:    $t_i = t_i + active\ duration$;
13:    if $t_i > beacon\ interval\ (BI)\text{-}active\ duration$;
14:      self-admission failure;
15:      return to step 2;
16:    else
17:      sense the channel again;
18:      return to step 8;
19:    end if
20:  end if
21: else
22:  return to step 3;
23: end if
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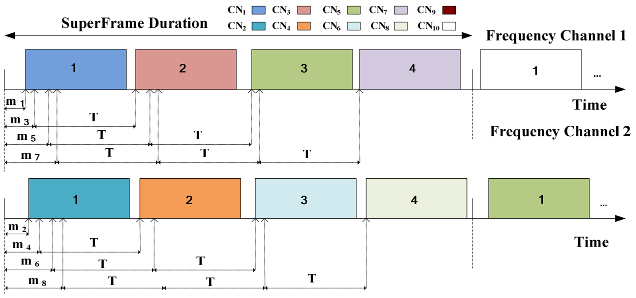

Fig. 2. The self-admission access process.

Each SCN randomly selects a Poisson random variable as the back-off value to contend for channels. The expectations of Poisson variable for each SCN are different, which depend on the average service rates of SCNs. The contending domain, that is, the carrier sensing range of a CN, is defined by the carrier sensing threshold γ. Figure 2 shows the self-admission access process of CNs $(BO - SO = 2)$, where there are $M_\mathrm{f}(M_\mathrm{f} = 2)$ frequency channels.

We extend the notion of a channel from spectral domain to spectral and temporal domain. As it is shown in Fig. 2, there are two frequency channels and the active period is a quarter of the superframe duration in superframe structure for the coexisting SCNs. Each active period contains T time slots. So, there are eight channels available in one contending domain. Suppose there are ten CNs to contend for channels in the same contending domain. When they find the channel is idle, they randomly produce their own back-off values $m_i\,(i = 1,\dots,10)$, respectively (m_1 is the lowest and m_{10} is the highest). The back-off value m_1 of the CN_1 is first reduced to 0 and the CN_1 listens to the channel again. When CN_1 finds the two frequency channels are idle, it accesses the frequency channel 1. When the back-off value m_2 of the CN_2 is reduced to 0 and CN_2 listens to the channel again, the CN_2 finds the frequency channel 2 is idle and accesses the frequency channel 2. When the back-off value m_3 of the CN_3 is reduced to 0, the CN_3 finds the two frequency channels are busy and backs off for an active period. After an active period, the CN_3 senses the channels again and finds the channels are idle. It accesses the frequency channel 1. The CN_4 also accesses the frequency channel 2 after backing off for an active period. The CN_5 accesses the frequency channel 1 after backing off for two active periods and so on. After the CN_8 accesses the channel, there is no time and frequency resource for CN_9 and CN_{10}. The two CNs suffer the self-admission access failure. For ease of understanding, this is a simple example that does not include collisions and the effects of correlation of time and space of the CNs. When we use TS-HCPP to model the coexisting self-admission access network, the two issues are both taken into account.

4.2 TS-HCPP Model for Heterogeneous Traffics in the Multi-channel Environment

Hard core point process (HCPP) is a powerful tool for modeling CSMA networks. However, the traditional HCPP suffers from the problem of underestimating the density of simultaneous transmitting nodes especially in a multi-channel environment. In this subsection, dealing with the underestimating problem, we propose a modified HCPP model called TS-HCPP, to model the renewal CSMA-based self-admission access process of networks.

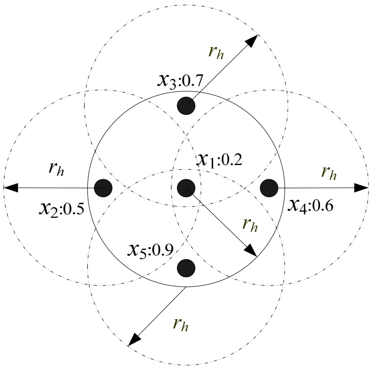

Fig. 3. The strong interference misjudgment problem of HCPP in multi-channel environment.

To explain the problem explicitly, we take the scenarios in Fig. 3 as an example to analyze underestimating issue of HCPP in the wireless network with multi-channels. As shown in Fig. 3, there are five points (five CNs), x_1 with mark 0.2, x_2 with mark 0.5, x_3 with mark 0.7, x_4 with mark 0.6 and x_5 with mark 0.9, respectively. The mark represents the back-off timer of CSMA, uniformly distributed between 0 and 1 [14]. M represents the number of channels, r_h is the radius of the carrier sensing of CNs. When $M = 2$, according to the traditional HCPP, only points x_1 and x_2 can be retained due to $x_1 < x_2 < x_4 < x_3 < x_5$. However, if the x_1 transmits in the first channel and other nodes transmit in the second channel, all five nodes can be retained. There is no mutual strong interference among x_2, x_3, x_4 and x_5 because the distance of each other is greater than exclusion distance r_h. We call the problem as "strong interference misjudgment". The other one of the underestimating problem of HCPP is shown in [14], [15]. The reason for this problem is that the traditional HCPP does not consider the correlation of time and space of the nodes. The two problems are significant for CSMA networks with high intensity or low carrier sensing threshold in multi-channel environment. The underestimated density of simultaneous transmitting nodes may directly affect the performance analysis.

As the above analyses, the traditional HCPP suffers from the problem of underestimating the density of simultaneously transmitting nodes especially in a multi-channel environment. It is very difficult to derive the closed expression of the probability of retaining nodes in which the three issues are considered, that is, collisions in self-admission access process, strong interference misjudgment and the correlation between time and space of nodes. As an alternative, we propose a modified HCPP called TS-HCPP to model the renewal CSMA-based self-admission process of SCNs, which evaluates the density of simultaneously active SCNs. We use multidimensional labels (i.e., the time tag and channel tag) to represent the back-off value, the time of accessing channel and the collisions of the network nodes, respectively. And we determine whether there exists a strong interference via the actual distance of the adjacent network nodes within the same contending domain. The selecting process is executed according to the time labels m_i of the nodes from low to high, which determines whether the node is retained.

Algorithm 2: The proposed TS-HCPP

```
input $M$;
variable $z \leftarrow$ '1' $T \leftarrow$ '1';
Generate a homogeneous $PPP\ \Phi$ with density $\lambda$;
Mark each point $x_i$ with an independent variable
    $m_i \sim P(u_i)$;
Mark each point $x_i$ with a tag $t_i$ with initial value '1';
Sort all the points according to $m_i$ in ascending order;
for $z \le M$ do
  for $x_i \in$ {all the sorted points} do
    for $x_j \in$ {all the sorted points} do
      if distance($x_i$, $x_j$) < $r_h$ && $m_i = m_j$ && $t_i = t_j = z$ then
        $t_j = 0$; $T = 0$;
      end if
      if $T=0$ then
        $t_i = 0$;
      end if
    end for
    for $x_j \in$ {all the sorted points} do
      if distance($x_i$, $x_j$) < $r_h$ && $t_i = t_j = z$ then
        $t_j \leftarrow$ '$z$+1';
      end if
    end for
  end for
end for
Remove all the points whose tags $t_i$ equal '$M$+1' or '0';
```

In the Algorithm 2, the selecting process starts with the point in ψ which has the smallest mark variable m_i and ends with the point in ψ which has the largest mark variable m_i in each round of selection. At the beginning, all the points in ψ are marked with $t = z = 1$, then tags t_i of points that are not retained in the selecting process are changed to $z + 1$ step by step until $z > M$. At the same time, the Algorithm 2 also considers collisions. t_i will be changed to "0" if there are points whose values of mark $m_i\,(i = 1,\ldots,n)$ are equal in the same contending domain. Finally, all the points which satisfy tags $t_i > M$ or $t_i = 0$ are removed and not considered in the following selecting process, namely, there are no enough frequency and time domain resources for data transmission.

The two random variables N and N_0 denote the number of the whole nodes and the retained nodes in Φ, respectively. The N_0 can be expressed as a sum of indicator functions as follows:

$$N_0 = \sum_{x_i \in \Phi} 1_{\{t_i = 1,\ldots,M\}} \ . \tag{1}$$

Then, the self-admission access probability for a CN in M available channels can be expressed as

$$P^{\mathrm{sa}} = \frac{N_0}{N}. \tag{2}$$

In a Rayleigh fading environment, for a carrier sensing threshold γ, the outage probability $P_{\mathrm{out}}(\gamma)$ of a generic CN is given by [11]. We define the transmission capacity of the network is the number of the SCNs that communicate normally in one superframe period. The transmission capacity in m channels can be expressed as

$$C = \lambda \cdot P^{\mathrm{sa}} \cdot \left[1 - P_{\mathrm{out}}(\gamma)\right]. \tag{3}$$

The TS-HCPP can solve the density underestimation problem of the traditional HCPP absolutely. It takes account for the distance of adjacent network nodes in the same contending domain, so the case of strong interference misjudgment does not appear. We use the time tag and channel tag to abstract the time and space correlation of nodes. Taking the scenario in Fig. 3 as example, the selecting process starts with x_1, the tag t_i of x_2, x_3, x_4, x_5 will be changed to '2' in the first round because m_1 is lower than m_2, m_3, m_4, m_5. Then x_2, x_3, x_4, x_5 will be selected in the second round because of the distance between the each other greater than hard core distance r_{h}.

4.3 The Optimum Combination of Access Parameters

In the proposed renewal CSMA-based self-admission access mechanism, the SCNs carrying heterogeneous traffics select different expectations of back-off counter value in the access process. In this subsection, based on TS-HCPP, we adopt the Algorithm 3 to obtain the optimum access parameters (i.e., expectations of back-off value) for heterogeneous traffics by the enumeration method in the case of limited number of WPANs.

According to the IEEE 802.15.4 standard, the beacon interval BI is given by $BI = aBaseSuperframeDuration$ $(aBSD) \times 2^{BO}$ symbols $= 60 \times 16 \times 2^{BO}$ symbols. Each symbol consists of 4 bits. The bit duration is 4 µs. $BI = 16 \times 60 \times 16 \times 2^{BO}$ µs. The superframe duration is $SD = aBSD \times 2^{SO}$ symbols $= 60 \times 16 \times 2^{SO}$ symbols. The total number of bits transmitted per superframe is given by $B_{\mathrm{s}} = 4 \times 60 \times 16 \times 2^{SO}$. Hence, the data rate served within each SCN is $V_{\mathrm{t}} = B_{\mathrm{s}}/BI = 2^{(SO-BO-2)}$ Mb/s. Each SCN is operating at self-admission access probability P_i^{sa}. The expression of the actual data transmission rate is $V_{\mathrm{t}} \times P_i^{\mathrm{sa}}$, without the consideration of collisions in the case of the low density of SCNs. Because heterogeneous traffics have different service rates and the same superframe structure, their requirements for self-admission access probabilities are different.

Heterogeneous traffics select different expectations of back-off counter value $u_{\hat{i}}$. Supposing that there are $\hat{n}$ kinds of SCNs, according to Algorithm 3, we can search for the optimum combination of $u_1, u_2, \ldots, u_{\hat{n}}$, which can meet the self-admission access probability requirements of SCNs and maximize the frequency resource utilization. The optimum combination of expectation needs to be recalculated if the number of types and densities of SCNs are changed. $[a,b]$ is the search range of the $u_{\hat{i}}$. $P_{\hat{i}}^{sa}$ represents the self-admission access probability requirements of the $\hat{i}$th kind of the SCNs.

Algorithm 3: The search method of the optimum combination of $u_1, u_2, \ldots, u_{\hat{n}}$

```
Input $P_{\hat{i}}^{sa}(\hat{i}=1,\ldots\hat{n})$, set $\phi_M$, $\varphi_{u_{\hat{i}}}$
for $u_{\hat{i}}(i=1,\ldots,\hat{n}) \in [a,b]$
    for $M \in [1, M_{\max}]$
        execute Algorithm 2;
        if $P_{\hat{i}}^{sa}$ is satisfied
            $M \in \phi_M$, $u_1, u_2, \ldots, u_{\hat{n}} \in \varphi_{u_{\hat{i}}}$; break;
        end if
    end for
end for
Select $u_1, u_2, \ldots, u_{\hat{n}}$, which makes the smallest $M$
    from $\varphi_M$ and the smallest sum of $u_1, u_2, \ldots, u_{\hat{n}}$
```

Maybe we may get several combinations which make the minimum number of channels at the same time. In order to improve channel utilization, back-off time should not be too long. So we choose the optimum combination which makes the smallest sum of $u_1,\ldots, u_n$.

In this section, we can obtain the total number of channels M^* required for the operation of the coexisting SCNs under heterogeneous traffics. Then, according to the superframe structure of SCNs, we calculate $M_t = 2^{BO-SO}$, that is, the number of SCNs which can align their superframes per frequency channel. Finally, we can get the number of required frequency channels $M_f = M^*/M_t$.

5. Simulation and Numerical Analysis

In this section, we evaluate the performance of the proposed TS-HCPP and validate the improvement in spectral efficiency of coexisting IEEE 802.15.4 networks under heterogeneous traffics. For the numerical evaluation (via Matlab), all SCNs locate in a circle area with the radius of 30 m. The path-loss exponent η is 4. M represents the number of channels. All the nodes transmit with the same transmit power $P_t = 1$ mW. In order to simplify the analysis, we ignore the impact of noise because the noise power is much lower than the interference power [21].

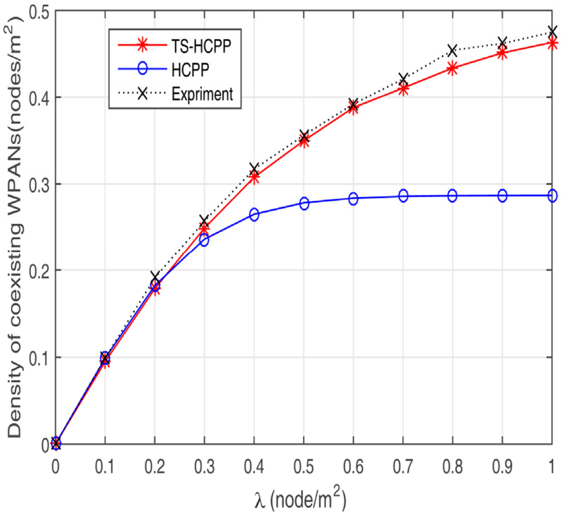

Fig. 4. Density of coexisting WPANs versus the initial density.

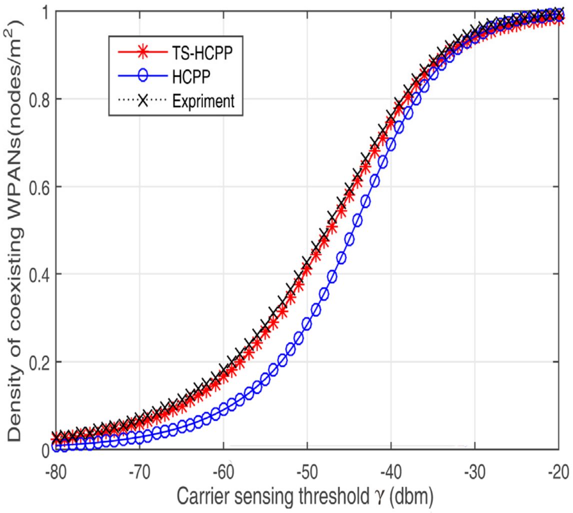

Fig. 5. Density of coexisting WPANs versus carrier sensing threshold.

One can see from Fig. 4 that the density of coexisting networks increases along with the density λ of the parent PPP Φ when $M = 4$. It is found that the densities of coexisting networks evaluated by the traditional HCPP and the proposed TS-HCPP are similar in the region with low PPP density (i.e., λ). However, when λ is greater than 0.3 node/m^2, TS-HCPP evaluates more coexisting networks than the traditional HCPP. And the density of coexisting networks evaluated by traditional HCPP remains unchanged, which implies the underestimation problem of the traditional HCPP is more serious in the region of larger λ. We can see the density of coexisting networks evaluated by TS-HCPP well matches the value of experiment at all the values of λ.

In Fig. 5, it is presented that the density of coexisting networks increases along with the carrier sensing threshold in case that λ = 1 node/m^2 and $M = 2$. It is obvious that the coexisting networks of the TS-HCPP are more than the traditional HCPP for most values of carrier sensing threshold. When the carrier sensing threshold of CN is smaller than –35 dBm, the underestimation problem of traditional

HCPP is serious. When the carrier sensing threshold of CNs is large, the sensing range is small and the number of SCNs in the same contending domain is small. The underestimation problem of traditional HCPP is not obvious. Therefore, Fig. 4 and Fig. 5 demonstrate that in terms of the density of coexisting WPANs, the theoretical results obtained by the proposed TS-HCPP can match the experimental results in different initial densities and carrier sensing thresholds, while the traditional HCPP cannot. Additionally, it is indicated that the TS-HCPP is capable of modeling the coexisting renewal CSMA-based self-admission access process for IEEE 802.15.4 networks in multi-channel environment.

In Fig. 6, it has been given that the transmission capacity increases along with expectation u. Taking channel utilization into account, the value of expectation u is not too large. As we can see from Fig. 6, the transmission capacity almost remains the same when u is greater than 15. Hence, in Algorithm 3, if there are $\hat{n}$ kinds of traffics, the expectation u of back-off counter value of the CNs is 15, whose requirement of the data transmission rate is the largest, that is, the requirement of self-admission access probability is the highest.

Assuming that there are 3 kinds of traffics, traffic A, traffic B, and traffic C, respectively. Their demanding self-admission access probabilities are 0.8, 0.7, 0.6, respectively. According to Algorithm 3, we can obtain the optimum combination of access parameters (15, 19, 24). As shown in Fig. 7, by the Algorithm 2, the self-admission access probabilities of all the SCNs can meet their requirements, when the expectations of back-off counter value of the three kinds of traffics are 15, 19, 24, respectively.

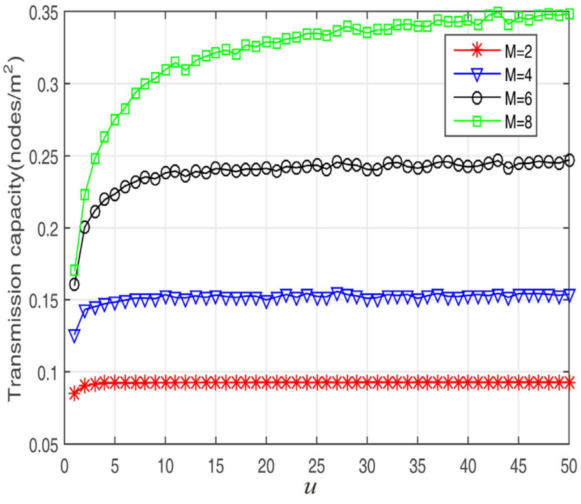

Fig. 6. Transmission capacity versus expectation u.

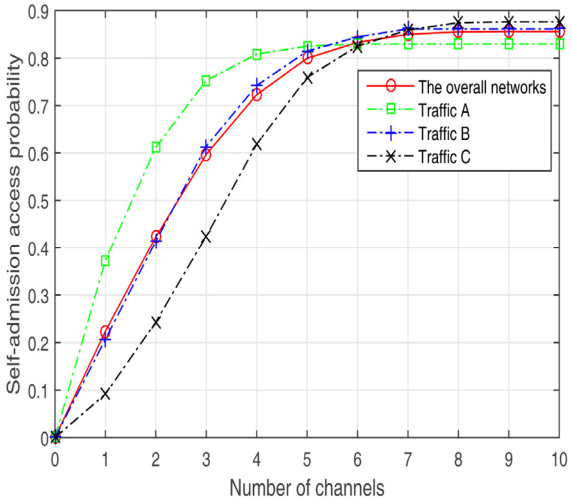

Fig. 7. Self-admission access probability versus the number of channels.

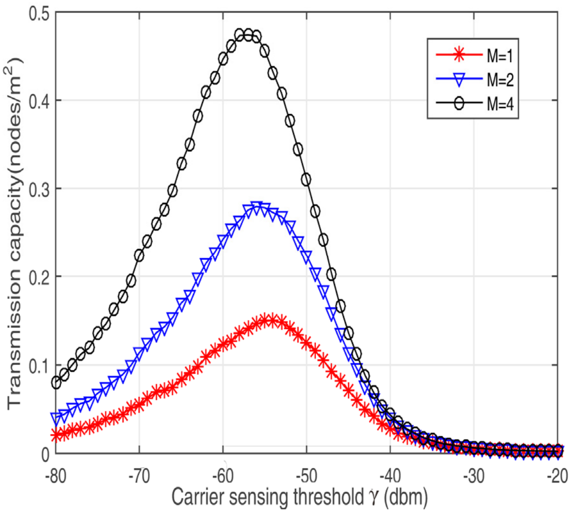

Fig. 8. Transmission capacity versus carrier sensing threshold in M channels.

When the density is 0.5 nodes/m^2, in the renewal CSMA-based self-admission access protocol, only four channels are required to meet the operations of all kinds of the SCNs. If access behaviors of all the SCNs are the same, the access probabilities are the same. In the case, as shown in Fig. 7, we need five channels to meet the communication requirements of all the SCNs. That is, the self-admission access probability of the overall network is not less than 0.8. This reveals an improvement in spectral efficiency of coexisting IEEE 802.15.4-based networks under heterogeneous traffics in renewal CSMA-based self-admission access protocol.

Figure 8 shows the transmission capacity of the proposed TS-HCPP versus the carrier sensing threshold γ in M channels. The parameters are as follows: $\lambda = 0.5$ node/m^2, $R = 1$ m, and $1/\mu = 0.5$. The time of interest is one superframe period. It can be seen that the transmission capacity cannot grow exponentially with the growing exponentially number of channels. Hence, the result in one channel cannot be suitable for the multi-channel analysis of renewal CSMA-based self-admission access networks. This observation illustrates the importance of the analysis of multi-channel self-admission networks. From Fig. 8, carrier sensing threshold is approximately –56 dBm, which maximizes the spatial reuse.

6. Conclusion

In this paper, we designed a spectrum-efficient self-admission access mechanism and addressed the underestimation problems of tradition HCPP in multi-channel analysis for coexisting WPANs. We proposed the TS-HCPP to model the renewal CSMA-based self-admission access process of coexisting IEEE 802.15.4-based networks under heterogeneous traffics. The results showed that the proposed TS-HCPP was superior to HCPP in terms of modeling the self-admission access network based on IEEE 802.15.4. The advantage of the TS-HCPP was more significant when the initial density became large or the carrier sensing threshold became small. For heterogeneous traffics, it was not necessary that all the coexisting WPANs operate in the same access behavior, which was a waste of frequency resources. In the renewal CSMA-based self-admission access protocol, we met the communication requirements of heterogeneous traffics with the different access behavior, and maximized the frequency resource utilization. Our work provided an important guide for the network layout.

In our proposed TS-HCPP, on one hand, we assumed that one active link always existed in each SCN during its active period. It was not consistent with the scenario of coexisting IEEE 802.15.4 networks with light load. On the other hand, we did not considered the difference of transmission power among SCNs. For these two points, in the future, we desire to optimize the TS-HCPP to model coexisting IEEE 802.15.4 networks, and investigate the power control strategy to improve transmission capacity in the renewal CSMA-based self-admission network.

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