An Optimization Technique of Spatial Reuse for Communication in Smart City Environment

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Abstract. In the application scenario of smart city, there exist many portable mobile devices that communicate in Wi-Fi technique, so communication conflicts among them are unavoidable and lead to low network performance and high energy consumption. To address this problem, this paper studies the optimization method of spatial reuse based on dynamic control of transmit power. Considering the metric of spatial reuse factor, this paper explores how to select the proper transmission radius and power to decrease the adverse effects from the hidden terminals and the exposed terminals. By setting the frame control field in the MAC layer frame according to the received signal strength, the method can adaptively adjust the transmission power of the communication nodes pair to maintain the reception power in the appropriate range. Through the simulation experiment in NS-2, the feasibility and effect of the optimization method for spatial reuse and energy saving are verified.

Keywords: Smart city · Power control · Communication conflict · Spatial reuse

1 Introduction

In the wireless network for smart city environment, many Wi-Fi based smart devices share a common wireless channel and operate independently; thus, communication collisions among them may happen frequently, these will affect effective utilization of precious resource of space and time [1]. Moreover, as these devices have limited energy supply, unnecessary energy consumption will shorten the effective network lifetime [2]. To address these problems, a optimization method for spatial-reuse based on adaptive power control is proposed. This method can achieve the dynamic adjustment of transmit power and communication radius based on the received signal strength. Thus, wireless nodes in the network can avoid the problems such as the low ratio of spatial utilization caused by the exposed terminals and communication collision caused by the hidden terminals, and yield improved network availability and less energy consumption.

The rest of this paper is organized as follows. Section 2 analyzes the effect of power control and the influence of propagation radius on spatial reuse. Section 3

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proposes the method for implement spatial reuse based on power control. Section 4 conducts the simulation evaluation for the proposed method. Last, Sect. 5 gives the conclusions.

2 The Analysis on Optimal Spatial Reuse

2.1 The Effect of Power Control

Generally the two-ray ground reflection model [3] is applied to describe the characteristics of channel fading in the smart city environments. In this model, the total received signal strength is the superposition of the direct signal strength and the reflected signal strength. Thus, the reception power of this model is

$$P_r = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4} \tag{1}$$

In (1), P_t and P_r are the transmission power and reception power respectively, G_t and G_r are the gains of transmitting antenna and receiving antenna respectively, h_t and h_r are the heights of transmitting antenna and receiving antenna respectively, and d is the propagation distance.

As can be seen from (1), when P_r is constant, P_t is directly proportional to d^4, indicating that even minor increase of distance between the communication nodes can result in the significant increase of P_t. If the constant P_t is used, it will be impossible for the communication to get adapted to the influence of change in propagation distance. Thus, the multi-level power adjustment technique can reduce the energy consumption and improve the network performance:

(1) when the communication distance is shortened, both communication sides can reduce P_t to save energy consumption and reduce interference against other nodes.
(2) when the communication distance is lengthened, both communication sides can increase P_t to keep the communication connection stable, and avoid such processes as route reselection and reconnection as a result of the excessively low signal strength.

2.2 The Influence of Propagation Radius on Spatial Reuse

The RTS/CTS mechanism in IEEE 802.11 [4] can overcome the hidden and exposed terminal problems to a certain extent, but the mechanism is not effective and cannot guarantee QoS when nodes can move freely. When a connection is established between a pair of nodes through the RTS/CTS interaction, the DATA/ACK packet communication can be carried out. Other nodes newly entering the communication range may be ignorant of the RTS/CTS interaction happened just now and send their own data, thus, giving rise to communication collision. This is known as the invading terminal problem, which essentially refers to the hidden and exposed terminal problems occurring randomly during the dynamic movement of nodes. According to (1), for a certain P_t, P_r

is set to be equal to the minimum power required for correctly receiving packets, which is labeled as RXThresh with default value of 3.652×10^{-10}W. The corresponding communication radius R_t represents the maximum communication radius needed for correctly receiving packets in the absence of interference.

We assume that the interference exists in the channel, the communication is going on between nodes A and B, the transmission power of the interfering node C is P_{ti}, the P_i is the interfering signal power received by node A from node C, the gains and heights of all antennas are identical, the SNR threshold is label as SNR_THRESH, the distance between nodes A and C is r, and that between nodes A and B is d. It can be derived that, to correctly receive packets between nodes A and B, the SNR must satisfy (2).

$$SNR = P_r/P_i = P_t r^4 / P_{ti} d^4 \geq SNR\_THRESH \tag{2}$$

If $P_{ti} = P_t$, $r \geq \sqrt{4}SNR\_THRESH \cdot d$ can be derived, so $r_{th} = \sqrt{4}SNR\_THRESH \cdot d$ is set as the critical radius of the interfering signal, and other nodes beyond this radius will not interfere against A. If the relative distance d between nodes is given, r_{th} can also be determined. If different values of P_t are used for the nodes, there will be different values of R_t accordingly [5]. According to the correlation between r and R_t, two conditions as shown in Fig. 1 are concluded as follows.

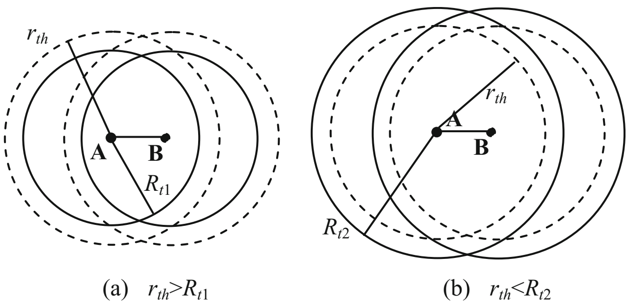


Fig. 1. Interference coverage under different conditions

(1) Figure 1(a) corresponds to the hidden terminal problem [6]. When the communication radius is smaller than the interference range, i.e., $R_{t1} < r_{th}$, the nodes inside the two dashed circles and outside the two solid circles may affect the normal communication between nodes A and B.
(2) Figure 1(b) corresponds to the exposed terminal problem. When the communication radius is larger than the interference range, i.e., $R_{t2} > r_{th}$, the nodes inside the two solid circles and outside the two dashed circles are covered by communication signals, but in fact these nodes will not affect the normal communication between nodes A and B.

For the sake of simplicity, only the case of single-hop links is considered, and the Spatial Reuse factor (*SRI*) is defined as the ratio of the total area that may generate interference against communication to the total area covered by the signals of both communication sides, i.e., the ratio of the total area of the two dashed circles to the total area of the two solid circles in Fig. 1. It represents the efficiency of spatial reuse. When *d*/*Rt* is set as a variable and SNR_THRESH = 10, the expression of *SRI* can be written as

$$SRI = \frac{13.4247(d/R_t)^2}{6.28 + (d/R_t)\sqrt{1-(d/R_t)^2/4} - 2\arccos[(d/R_t)/2]} \quad (3)$$

The curve of *SRI* [7] is drawn in Fig. 2. As can be seen from Fig. 2, to achieve the best level of spatial reuse (i.e., the point on the curve where *SRI* is 1), $d = 0.56R_t$ is required. At this point, both the hidden and exposed terminal problems do not exist, and the optimal reception power is P_{rop} = 10*RXThresh. The curve where $SRI > 1$ corresponds to the hidden terminal problem, and that where $SRI < 1$ corresponds to the exposed terminal problem. The communication radius can be changed to achieve the optimum state by adaptive power control, thus to make the optimal utilization of the wireless channel and avoid channel collision.

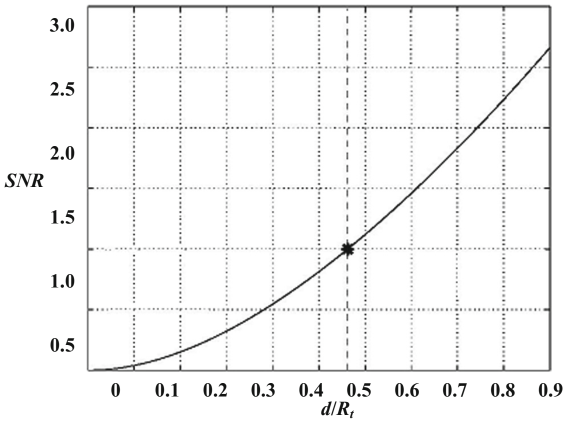


Fig. 2. SRI change with d/R_t

3 The Implementation of the Optimal Spatial Reuse

3.1 The Interference-Aware Setting of Reception Power Range

Given that small-scale fading effect exists in the wireless channel and the P_r of each packet changes randomly, it is difficult to accurately control P_t in reality. Considering that we try to achieve $P_r = P_{rop}$, and generally $P_{ti} \neq P_t$ in actual situations, the value of P_{rop} depends on the specific situations.

(1) When $P_{ti} < P_t$, strong communication signals between nodes lead to the exposed terminal problem, and the channel may not be fully utilized, but the communication without interference can be realized as no hidden terminal problem exists.
(2) When $P_{ti} > P_t$, there are stronger interference signals; at this moment, the exposed terminal problem disappears while the hidden terminal problem exists, and the communication interference may be generated.

One feasible solution is to limit P_r within a proper range to generate less interference to other communications and achieve the optimal spatial reuse. According to (2), when $P_{ti} = kP_t$ ($0 < k < 5$), we assume the interference is tolerable, and the optimal reception power is $P_{rop} = 10\ k$*RXThresh. Thus, the desired reception power range is set as (4).

$$P_r \in \begin{cases} [10k \times RXThresh, 10RXThresh] & 0 < k \le 1 \\ [10RXThresh, 10k \times RXThresh] & 1 < k < 5 \end{cases} \tag{4}$$

When P_{ti} is very strong (corresponding to $k \geq 5$), it is impossible and unnecessary to adjust transmission power for continuing communication. In such case, the "Wait-to-Restore" mechanism can be employed, and the relevant steps include:

(1) suspend the communication and saving the communication state;
(2) set the timer according to the NAV field from the received interfering packet;
(3) enter the sleep state and wait until the communication of interference nodes finishes;
(4) after the waking up of relevant nodes, complete the paused transmission and reception of the remaining packets.

3.2 The Interaction Mechanism Between Nodes

Power control is realized by the feedback mechanism. Based on the IEEE 802.11 protocol, the corresponding "power adjustment information piggyback" function is added to the MAC layer, and P_t is modified synchronously at both communication sides. The specific conditions are as follows:

(1) When the sender transmits DATA packet to the receiver, the receiver judges if it is necessary to adjust P_t according to the P_r from the obtained packets. The receiver sets the instruction requiring the sender to carry out power control in the frame control field of ACK packets, and sends the ACK packets with the modified P_t.
(2) When the receiver replies to the sender with an ACK packet, the sender acts as the feedback provider who will judge whether it is necessary to adjust P_t according to the P_r of the received ACK packet. It sets the instruction requiring the receiver to carry out power control in the frame control field of the next DATA packet, and sends the DATA packet with the modified P_t.

3.3 The Trigger Mode of Power Control

Since the signal strength of packets can objectively reflect the communication links' quality, it can be used as a reference for power control. As the actual P_r may be different from the theoretical value derived from (1) due to the small-scale fading effect, it is necessary to consider the macroscopic statistical characteristics of small-scale fading and use the statistical average of the recently received packets to represent the effective P_r value. Therefore, the feedback provider maintains a queue of PrRec[N], stores the P_r values of N recently received packets [8]. Further the feedback provider designates two counters, i.e., *LoCnt* and *HiCnt*, to represent the number of packets when P_r is below the lower limit (10*RXThresh) and above the upper limit (50*RXThresh) respectively. Besides, two dynamic count ranges for *LoCnt* and *HiCnt*, i.e., R_L and R_H, are initialized with N respectively.

When a packet is received, the range that this packet's P_r falls into is judged, and the corresponding counter is updated if necessary. The relevant rules to be observed are:

(1) When the counter value exceeds the threshold (0.5*R_L or 0.5*R_H), the new transmission power and the frame control field of feedback packet are set.
(2) When the counter value is between the threshold and 0.2 N, the binary exponential back-off process is used to reduce the length of the count range to reflect new states.
(3) When the counter value is below 0.2 N, the length of the count range is increased linearly until the range restores to N.

Figure 3 shows the detailed process on how a newly received packet is processed.

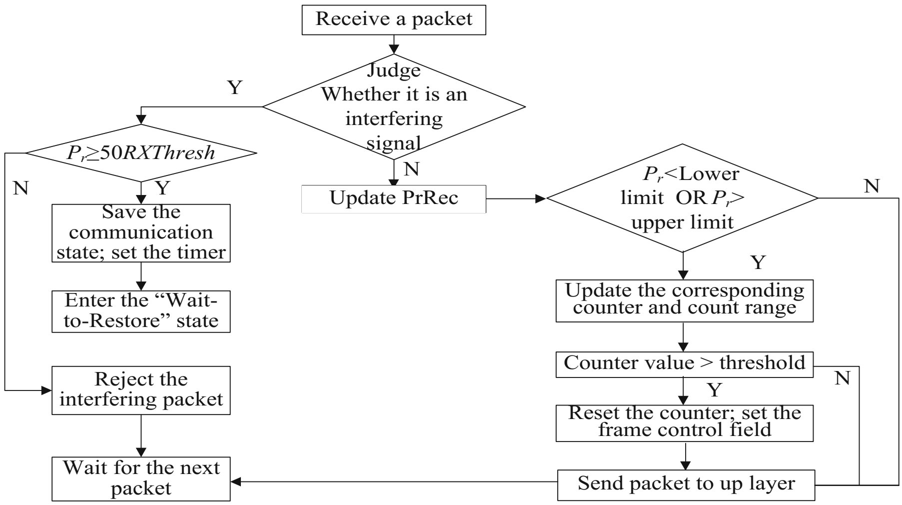


Fig. 3. The packet processing process

3.4 The Calculation of New Transmission Power

For setting the frame control field, we take P_r of the latest M packets from RrRec [N] and the previous transmit power P_{t0} as the reference for calculating new transmission power. Considering $d \propto \sqrt{4}P_t/P_r$, we define the equivalent distance d_e for this M packets as

$$d_e \propto \frac{1}{M}\sum_{s=1}^{M}\sqrt[4]{\frac{P_{t0}}{(P_r)_s}} \quad (5)$$

According to (1), we obtain the new optimal transmit power P_{tn} in (6).

$$P_{tn} = 10RXThresh(\sqrt[4]{P_{t0}}\frac{1}{M}\sum_{s=1}^{M}\frac{1}{\sqrt[4]{P_{rs}}})^4 \quad (6)$$

4 Numerical Evaluation

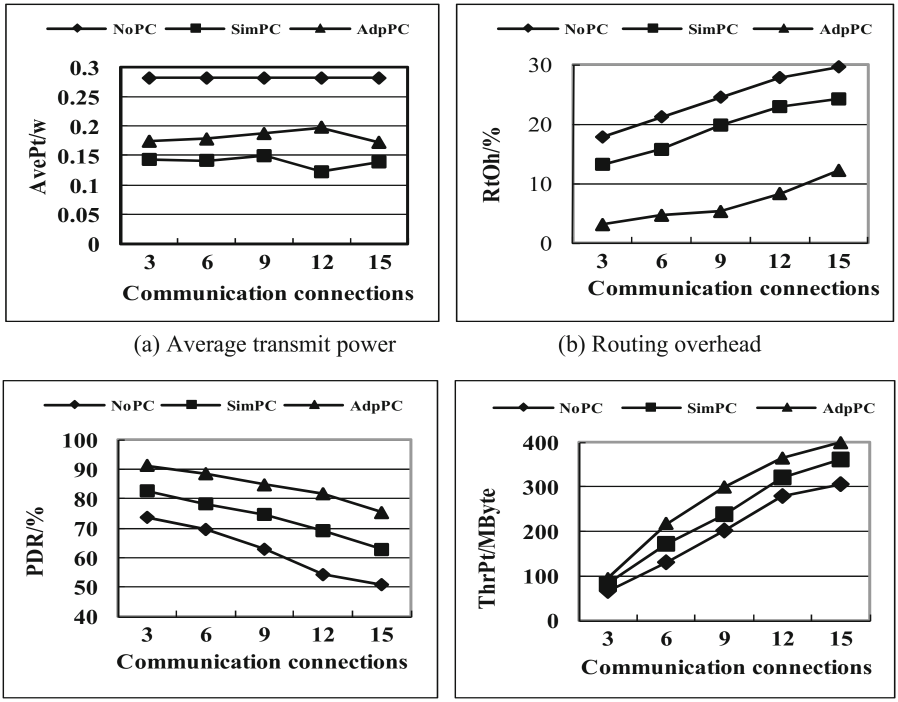
4.1 The Settings of Simulation

The network performance is analyzed among three schemes with the simulation experiment in NS-2 [9], the schemes include: the scheme that transmits by default transmission power of 0.2818 W without power control (NoPC), the scheme using the 10 preset power levels for multi-level power control (SimPC) [10], and our proposed scheme using the adaptive power control for spatial reuse optimization (AdpPC).

The nodes movement scenario is set as follows: 36 nodes move randomly at the speed of 5 m/s in a 1200 m*1200 m area. There are five traffic scenarios of different traffic volumes, i.e., 3, 6, 9, 12 and 15 traffic flows respectively for each scenario. Each flow uses the constant bit rate (CBR) sources and the transmitting rate is 1000 packets per second. The duration of each flow is 25 s and the total simulation time lasts for 100 s. For different schemes, the following four performance indexes are calculated: (1) *AvePt* – the average transmit power; (2) *RtOh* – the routing overhead, i.e., the ratio of the number of total routing packets to the number of total received packets; (3) *PDR* – the packet arrival ratio; (4) *ThrPt* – the network throughput measured in Mega Byte.

4.2 Simulation Results and Analysis

The results of simulation are shown in Fig. 4. As can be seen from Fig. 4(a), SimPC achieves the best energy-saving effect as it can use extremely low P_t when the communication distance is short. The energy-saving effect achieved by AdpPC is also obvious, although slightly inferior to SimPC, for this scheme can restrict the increase of P_t by confining P_r of the packets below the upper limit. According to Figs. 4(b) and (c), AdpPC achieves the lowest *RtOh*, the highest *PDR*, and the least collision arising from hidden terminals. Following it is SimPC which can also control P_t to a certain degree to reduce communication interference. As the communication traffic volume increases, there is more severe communication collision, which will increase *RtOh* and reduce *PDR*. From Fig. 4(d), it can be seen that AdpPC prevails over other schemes. It achieves the optimal network performance by appropriately adjusting the communication radius to eliminate collision and making the best use of the limited space.



(a) Average transmit power (b) Routing overhead

(c) Packet arrival rate (d) Network throughput

Fig. 4. Simulation results

5 Conclusion

In the proposed method, the channel condition is obtained based on the signal strength of the received packets, so the data sender can get accurate guidance to use appropriate power for communication and effectively utilize space and energy. The topic to be explored in future include the following. In-depth analytical work needs to be conducted on spatial reuse in the case of complex topology structures. Besides, the proposed method can also be used in conjunction with other optimization techniques for spatial reuse, such as dual-channel, directional antennas and cognitive access.

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