Statistical Analysis of Interference Avoidance based on Multi-Frequency RTS/CTS Cognitive Radio

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Abstract—**In order to avoid interference to primary users within cognitive radio, a multi-frequency RTS/CTS scheme is studied in this paper. Assuming that channels suffer from Rayleigh fading and shadowing, we derive a closed-form of interference avoidance criterion based on multi-frequency RTS/CTS scheme. Simulations are carried out to validate the theoretical formulation. Results show that with the interference avoidance criterion based on the multi-frequency RTS/CTS scheme, interference can be rationally avoided. Propagation impacts on the criterion are also discussed and the analysis indicates that the required transmit power of the primary receiver is affected heavily by propagation characteristics.**

Keywords- cognitive radio; interference avoidance; multi-frequency RTS/CTS

I. INTRODUCTION

According to the Federal Communication Commission (FCC) reports, the shortage of frequency spectrum is caused primarily by the inefficient allocations, which leads to the fact that even when some applications suffer from the lack of spectrum, there is still idle capacity in the other bands [1]. As an emerging technology to deal with the spectrum under-utilization for the increasing wireless applications, *cognitive radio* (CR) has gained much attention [2]. The concept of CR refers to an intelligent wireless communication system wherein the secondary users (SUs) are equipped with the ability of spectrum sensing and capable to access the vacant spectrum resources not being utilized by the incumbent users (primary users, PUs). In essence, due to the priority of the PUs, SUs are obliged to keep sensing the primary spectrum activities continuously and avoid the interference to the PUs at all times.

However, owing to the lack of interactions between the PUs and the SUs, precise spectrum sensing over a wide span of spectrum is practically infeasible through local observations and hidden terminal problem is unpreventable due to the randomness of the radio propagation [3]. In traditional wireless networks, CSMA (Carrier Sense Multiple Access) with RTS/CTS (Request to Send/Clear to Send) handshake is applied to solve the hidden terminal problem [4]. Besides, the RTS/CTS handshake accessing multiple separated slices of the frequency bands has been proposed to improve the spectrum efficiency of the RTS/CTS handshake scheme [5]. In this paper, we consider a multi-frequency RTS/CTS CR scheme directly targeting at taking advantages of both the ability of solving hidden terminal problem with the RTS/CTS hand-shake and the high efficiency of the frequency utilization in cognitive radio. On the other hand, although a considerable amount of researches have been done to the propagation influence on CR [6], little work has been conducted to the impacts of the propagation on the RTS/CTS scheme in CR. Subsequently, we devote special effort to the statistic analysis of the propagation issues and formulate the closed-form of a potent interference avoidance criterion based on the multi-frequency RTS/CTS scheme.

The remainder of this paper is organized as follow. In Section II, we form the problem and introduce the multi-frequency RTS/CTS CR scheme. Interference avoidance criterion and propagation impacts are investigated through statistical analysis in Section III. Finally, in Section IV, performance is evaluated and remarks are presented as well.

II. PROBLEM FORMULATION

A. Multi-frequency RTS/CTS CR scheme

For simple illustration, we consider a CR network wherein two SUs coexist with two PUs as showed in Fig.1. The solid and the dashed circles represent the coverage range of the primary transmitter (PU Tx) and the interference range of the secondary transmitter (SU Tx), respectively. When a primary receiver (PU Rx) lies in the common area of the coverage range and the interference range, it becomes a hidden receiver similar as the hidden terminal in wireless network. Namely, it could be solved with the conventional RTS/CTS handshake scheme, which assumes that the data and the control signals are transmitted with the same frequency. However, in the light of the actual conditions that the vacant or idle spectrum bands are discontinuous and numerous, the usage of multiple frequencies should be taken into consideration while appealing to the RTS/CTS handshake. Hence, within this paper we suggest a multi-frequency RTS/CTS handshake scheme for CR. Fig. 1 schematically shows the procedure of the suggested scheme: (1) The PU Tx will transmit a short RTS packet before its transmission. (2) The potential PU Rx responds to PU Tx with a CTS packet authorizing the PU transmissions and meanwhile informing the neighbouring SU Tx to restrain its transmitting.

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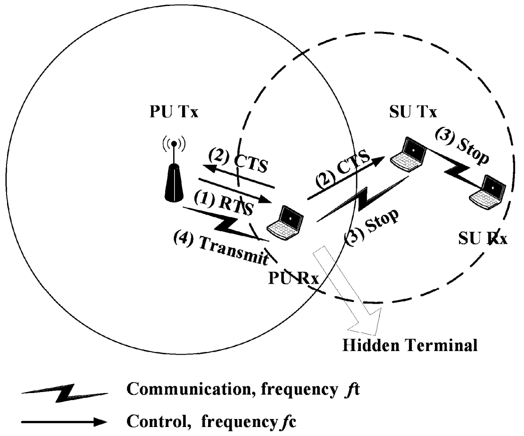

Figure 1. Multi-frequency RTS/CTS CR scheme.

(3) The SU Tx abstains from the band being occupied immediately upon receiving the CTS packet and keeps silent for the duration of the PU communications. (4) The PU Tx starts the transmission.

Different from the traditional RTS/CTS handshake, we assume that: the control signaling (RTS/CTS packets) is transmitted with a fixed control frequency f_c shared by all the PU and SU terminals whereas data is transmitted with the communication frequency f_t differing from the control frequency f_c; CTS packets contain not only the signaling but also the information about the PU communications, e.g. the duration, the communication frequency f_t, etc; all the terminals are equipped with the functions of transmitting and sensing of the control signaling; the sensing of the control signaling at control frequency f_c is carried out during all the time. Obviously, with the multi-frequency RTS/CTS scheme, the SU Tx can acquire the occupied frequency bands from the CTS packets and infer that how soon they can be released. Subsequently, the SU Tx might pick up frequencies other than occupied ones and starts the SU communications. Thereupon, the multi-frequency RTS/CTS scheme enables the SU communications coexist with the PU communications without interfering the PUs while improving the spectrum efficiency.

B. System Model

Intuitively, with the scheme, the hidden terminal problem would be solved theoretically and the interference to the PUs can be avoided with considerably large CTS signaling power from the PU Rx. But this is true only in the sense that the distance is deterministic and the fading are not involved. On the contrary, in the practical wireless environment, subject to the fading and the random locations of the SUs, it is stochastic to determine whether the signaling and the data are perceived at the intended receivers or not. Therefore interference occurs.

It should be stressed that the interference at the PU Rx is caused primarily by the SU Tx. Hence, we focus on the links between the PU Rx and the SU Tx and their statistics. For the sake of the mathematical convenience, consider a PU Rx in the center of a circular region of radius R_2 (see Fig.2). The SU Tx is located uniformly in an annulus with the outer radius R_2 and the inner radius R_1 centered on the PU Rx. The use of annulus restricts the length of links from being too small, which matches the physical reality.

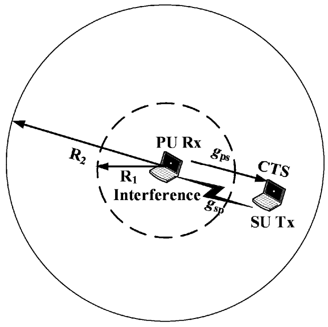

Figure 2. System model.

In this paper, assume the channel including the path loss, shadowing and multipath fading. To introduce the required notations, we first consider the power attenuation and the fading of the transmit power due to the propagation characteristics.

Let P_t be the transmit power in dBm. The corresponding received power P_r in dBm can be expressed as:

$$P_r(\text{dBm}) = P_t(\text{dBm}) + g(\text{dB}) \tag{1}$$

and we have the channel gain g expressed by:

$$g = \frac{|h|^2}{PL \cdot L} \tag{2}$$

where the variance L=$10^{S/10}$ is for the lognormal shadowing, and S is zero mean Gaussian with the standard variance σ. h is for the multipath fading. For unit power Rayleigh channel the channel gain is $|h|^2$ with exponential PDF given by:

$$f_{|h|^2}(x) = \frac{1}{2} e^{-\frac{1}{2}x} \tag{3}$$

As for the path loss PL, we here apply the Okumura-Hata Model [7, 8] as the empirical mean path loss model depending on the antenna height, carrier frequency, distance, etc. Although the suggested scheme is not restricted to the environments in which Okumura-Hata model was made, it is suitable for a basis performance analysis. Then PL in dB can be expressed by:

$$PL(r)(\text{dB}) = A + B\log_{10}(r) \tag{4}$$

where

$$\begin{aligned} A &= 69.55 + 26.16\log_{10}(f) - 13.82\log_{10}(h_t) - a \\ B &= 44.9 - 6.55\log_{10}(h_t) \\ a &= \begin{cases} 8.29(\log_{10}(h_r))^2 - 1.1 & f < 400 \text{ MHz} \\ 3.2(\log_{10}(h_r))^2 - 4.97 & f \geq 400 \text{ MHz} \end{cases} \end{aligned}$$

here h_t and h_r represent the height of the transmit and receive antennas, respectively. f is the carrier frequency and r is the distance between the transmitter and the receiver.

III. STATISTICAL ANALYSIS OF INTERFERENCE AVOIDANCE CRITERION

Practically, even when there is SU communication co-existing with PU communication, interference might not be perceived at the PU Rx owing to the randomness of the received power. In other words, interference occurs at the PU Rx only in the condition that SU communication is detected at the PU Rx after CTS signaling has been missed by the SU Tx based on the suggested scheme. Accordingly, after the PU Rx increasing the transmit power of CTS signaling to ensure the detection, the SU Tx withdraws its transmission, viz. interference, upon detecting the CTS signaling. Still, due to the randomness of the received power, interference could not be eliminated completely and we aim to conduct the statistic analysis of interference avoidance based on the suggested scheme.

Notation: The subscripts $_\text{p}$ and $_\text{s}$ denote the transmit power or received power at the PU Rx and the SU Tx, respectively. The subscripts $_\text{ps}$ and $_\text{sp}$ stand for the links from the PU Rx to the SU Tx and the reverse one.

For uniformly distributed SU Tx, the distance between the SU Tx and the PU Rx r_sp has the PDF of:

$$f_{r_\text{sp}}(r_\text{sp}) = \frac{2r_\text{sp}}{R_2{}^2 - R_1{}^2}, \qquad R_1 \le r_\text{sp} \le R_2 \tag{5}$$

Because of the distribution of the distance, randomness has been brought into the PL_sp. Thus, from (4) and (5), the PDF of PL_sp in dB can be written as:

$$f_{PL_\text{sp}(\text{dB})}(x) = \frac{2\ln 10}{B_\text{sp}(R_2^2 - R_1^2)} 10^{\frac{2(x-A_\text{sp})}{B_\text{sp}}},$$

$$PL_\text{sp}(R_1)(\text{dB}) \le x \le PL_\text{sp}(R_2)(\text{dB}) \tag{6}$$

Therefore, the PDF of $P_{r\text{p}}$ in dBm can be deduced as:

$$f_{P_{r\text{p}}(\text{dBm})}(x) = \frac{(\ln 10)^2}{10\sqrt{2\pi}\sigma_\text{sp} B_\text{sp}(R_2^2 - R_1^2)} \times \int_{PL_\text{sp}(R_1)}^{PL_\text{sp}(R_2)} \int_{-\infty}^{\infty} 10^{\frac{x-P_{t\text{s}}(\text{dBm})+y+z}{10}} \times \exp\left(-\frac{10^{\frac{x-P_{t\text{s}}(\text{dBm})+y+z}{10}}}{2}\right) dz \times 10^{\frac{2(y-A_\text{sp})}{B_\text{sp}}} dy \tag{7}$$

With specific r_sp, PL_sp is a deterministic value $PL_\text{sp}(r_\text{sp})$ and the conditional PDF of $P_{r\text{p}}$ in dBm is formulated as:

$$f_{P_{r\text{p}}(\text{dBm})|r_\text{sp}}(x|r_\text{sp}) = \frac{\ln 10}{20\sqrt{2\pi}\sigma_\text{sp}} \times \int_{-\infty}^{\infty} 10^{\frac{x-P_{t\text{s}}(\text{dBm})+PL_\text{sp}(r_\text{sp})(\text{dB})+z}{10}} \times \exp\left(-\frac{10^{\frac{x-P_{t\text{s}}(\text{dBm})+PL_\text{sp}(r_\text{sp})(\text{dB})+z}{10}}}{2}\right) \exp\left(-\frac{z^2}{2\sigma_\text{sp}{}^2}\right) dz \tag{8}$$

The link from the PU Rx to the SU Tx can be defined similarly.

We assume that the data and the signaling can be detected if their received power are above the threshold ζ_s and η_p. The parameter ζ_s is the CTS detection threshold in dBm at The SU Tx, whereas the parameter η_p is the tolerable interference threshold in dBm at the PU Rx, which specifies the noise floor. Therefore, the probability that the SU Tx detects the signaling is:

$$P_\text{d}{}^\text{CTS} = \Pr(P_{r\text{s}} > \xi_s) = \int_{\xi_s}^{+\infty} f_{P_{r\text{s}}(\text{dBm})}(x)dx \tag{9}$$

and the probability that the PU Rx is interfered is:

$$P_\text{i}^\text{data} = \Pr(P_{r\text{p}} > \eta_\text{p}) = \int_{\eta_\text{p}}^{+\infty} f_{P_{r\text{p}}(\text{dBm})}(x)dx \tag{10}$$

Then, the probability of interference avoidance means the probability that the SU Tx can detect the CTS signaling under the condition that the PU Rx has been interfered. Therefore, we write it with formula as:

$$\begin{aligned} P_\text{avoid} &= \Pr(P_{r\text{s}} > \xi_s | P_{r\text{p}} > \eta_\text{p}) \\ &= \int_{R_1}^{R_2} \Pr(P_{r\text{s}} > \xi_s | r_\text{sp}, P_{r\text{p}} > \eta_\text{p}) f(r_\text{sp} | P_{r\text{p}} > \eta_\text{p}) dr_\text{sp} \\ &= \int_{R_1}^{R_2} \frac{\int_{\xi_s}^{\infty} f_{P_{r\text{s}}(\text{dBm})|r_\text{sp}}(x|r_\text{sp})dx \int_{\eta_\text{p}}^{\infty} f_{P_{r\text{p}}(\text{dBm})|r_\text{sp}}(y|r_\text{sp})dy}{\int_{\eta_\text{p}}^{\infty} f_{P_{r\text{p}}(\text{dBm})}(y)dy} f_{r_\text{sp}}(r_\text{sp})dr_\text{sp} \end{aligned} \tag{11}$$

By substitute $f_{Pr\text{p}(\text{dBm})|r\text{sp}}(P_{r\text{p}}|r_\text{sp})$, $f_{Pr\text{s}(\text{dBm})|r\text{sp}}(P_{r\text{s}}|r_\text{sp})$ and $f_{Pr\text{p}(\text{dBm})}(P_{r\text{p}})$ into (11), the closed-form of the probability of the interference avoidance can finally be obtained. From the derivation, we can deduce a conclusion that the probability is the function of $P_{t\text{p}}$, $P_{t\text{s}}$, R_1, R_2, ζ_s, η_p, etc. Since the requirements on the system design, transmit power of the SU Tx $P_{t\text{s}}$ is always bounded and the thresholds, ζ_s and η_p, are decided by the sensibility of the receivers. Moreover, the inner radius R_1 depends on the practical propagation environment. In brief, the probability of interference avoidance varies with the transmit power $P_{t\text{p}}$ and the outer radius R_2.

Here, we apply a minimum value P to the probability of the interference avoidance. The interference avoidance criterion can be expressed as:

$$P_\text{avoid} = \Pr(P_{r\text{s}} > \xi_s | P_{r\text{p}} > \eta_\text{p}) \ge P \tag{12}$$

where P is defined as the minimum probability of interference avoidance referring to some specific performance of the interference avoidance. According to the interference avoidance criterion derived in (12), while the other parameters are settled, the transmit power of the PU Rx $P_{t\text{p}}$ is dominant to satisfy a certain value of the interference avoidance probability P.

IV. PERFORMANCE EVALUATION

Let the SU Tx be uniformly distributed in a planar area bounded by an annulus centred at the PU Rx with the inner radius R_1 and the outer radius R_2. Besides, both the large scale and the small scale fading are taken into consideration. The default parameters are listed in Table I unless otherwise stated. It should be noted that parameters in Table I are used for performance evaluation only and may not be practical for the actual applications.

We firstly confirm the theoretical results with the simulation results. For this purpose, we have firstly plotted the required PU Rx transmit power P_{tp} versus the outer radius R_2 in Fig.3. The curve indicates that the theoretical results are verified to be identical with the simulation results for a given probability of interference avoidance P equals to 95%. In addition, the required P_{tp} increases with the outer radius R_2: as the outer radius R_2 increases from 100 meters to 8 kilometers, sufficiently large P_{tp} is required. However, for an extremely large R_2, assuming the SU Tx is distributed in a huge annulus, the required P_{tp} seems to approaches to a plateau. The reason is that the required transmit power P_{tp} keeps low when the SU Tx is located around the PU Rx since the CTS signaling can be detected easily. On the contrary, owing to the path loss, signal from very far area would be so small and rarely causes interference. Due to that, it is inferable that the required P_{tp} would converge to a certain value as R_2 is infinite. Besides, with the variation of P from 95% to 99%, Fig. 3 implies that more transmit power should be emitted as better performance of the interference avoidance are needed. The required transmit power shown in the figure is unrealistically large such as 50 to 70dBm. However it should be noted that the objectives of the analysis is to prove the validity of the presented formulation. The required transmit power depends on various parameters suggested in Eq.(12) and it can be appropriately designed by the selection of the values of these parameters.

In view of the consistency of the theoretical results and the simulation results as indicated in Fig.3, performance evaluations below are all demonstrated with simulation results without loss of generality.

Then, we examined several data to investigate how the propagation characteristics act on the performance of the interference avoidance. As revealed from the deduction, there are three impact aspects of propagation on the interference avoidance should be addressed. The first impact involves the median path loss. It is well known that there exists reversibility between the links according to the traditional RTS/CTS mechanism. Unlike that, within the suggested scheme, the path loss from the PU Rx to the SU Tx and the reverse one differs from each other in terms of the frequencies, which brings on influence to the application of RTS/CTS handshake and should be paid much attention to. Fig. 4 shows the relationship between the required P_{tp} and the communication frequency f_t. It can be found that the required P_{tp} declines as the f_t increases. The reason would be that the path loss of the interference increases with the communication frequency which relax the required transmit power to cover the less attenuation. In other word, in order to cut down the required P_{tp} and maintain the performance of interference avoidance, the SU Tx should choose the higher f_t.

TABLE I. SIMULATION PARAMETERS.

Communication frequency f_t	200MHz~5GHz
Control frequency f_c	1GHz
SU Tx transmit power P_{ts}	10dBm
CTS detection threshold ζ_s	-80dBm
Interference threshold η_p	-100dBm
Inner radius R_1	50m
Outer radius R_2	100m~8km

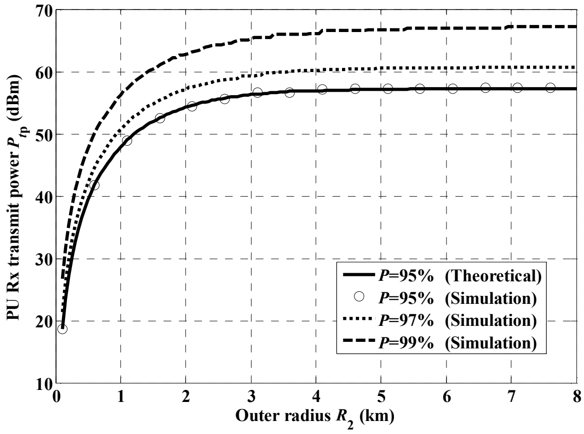

Figure 3. Theoretical and simulation results for interference avoidance (for P from 95% to 99%, f_t=1GHz).

The second impact relates to the shadowing [9]. Usually, signal detection is vulnerable to the shadowing correlation between the uplink and downlink [10]. Fig. 5 shows the impacts of the shadowing correlations between the links on the required transmit power where the standard deviation is 8dB. As is shown in the Fig. 5, it seems that there is almost no difference among the required P_{tp} while the SU Tx lies in the vicinity of the PU Rx. Nevertheless, in the case that the SU Tx is distributed in a huge area, while the links are totally correlated (ρ equals to 1) and absolutely uncorrelated (ρ equals to 0), the difference increases up to 16dB. Obviously, with the

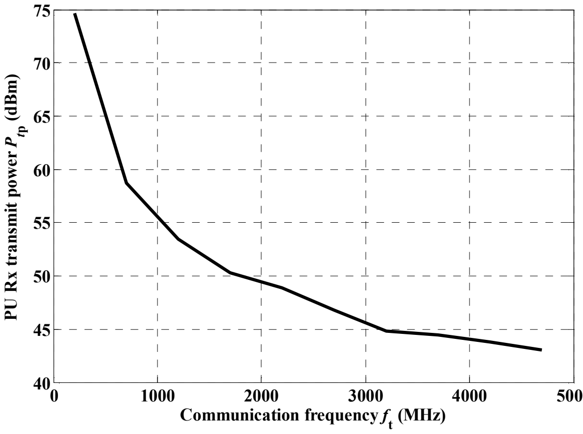

Figure 4. Impacts of path loss on required P_{tp}(P = 95%, R_2=8km).

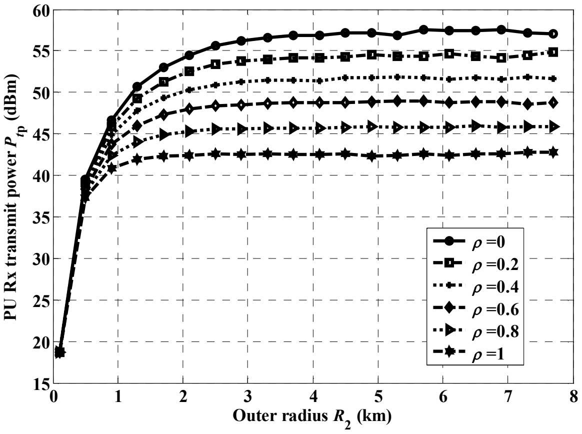

Figure 5. Impacts of shadowing correlation between links on required P_{tp} (P = 95%, f_t=1GHz, σ=8dB).

higher correlation, the required P_{tp} might be less and more margins of the transmit power should be set aside for less correlation.

The third aspect deals with the multipath fading. Assuming relatively small time delay spread value such as 0.1 μsec for a bad case scenario, the coherence bandwidth B_d, which is given as the inverse of the time delay spread, becomes 10MHz. Within the suggested scheme , even with relatively large B_d of 10MHz, the huge span of spectrum is considerably larger than the B_d resulting in the frequency selective fading and undesirably high transmit power are needed. It is undoubtedly infeasible in practical applications. To compensate the large required transmit power, for instance, diversity is useful to deal with the multipath fading. Several works deploying multiple antennas for signal detection in CR systems are presented in [11, 12]. Fig. 6 illustrates the effect of the receive diversity on the performance of interference avoidance. Here, shadowing is considered totally correlated whereas multipath fading is completely uncorrelated. As is shown in Fig.6, the reduction of the required transmit power nearly 8 dB is realized while the SU Tx lies in the vicinity of the PU Rx and more than 14 dB is achieved with the SU Tx distributed in a huge area.

V. CONCLUSION

In this paper, interference avoidance is studied based on multi-frequency RTS/CTS CR scheme. We derive a closed-form of the interference avoidance criterion base on the scheme as well as analyze the impacts of the radio propagation. It is shown that the transmit power of the CTS signaling is the dominant parameter to maintain the performance of the interference avoidance criterion. The simulation results indicate that the required transmit power of the PU Rx is affected heavily by propagation issues and more effective methods are appealed for to alleviate the required transmit power of the control signal.

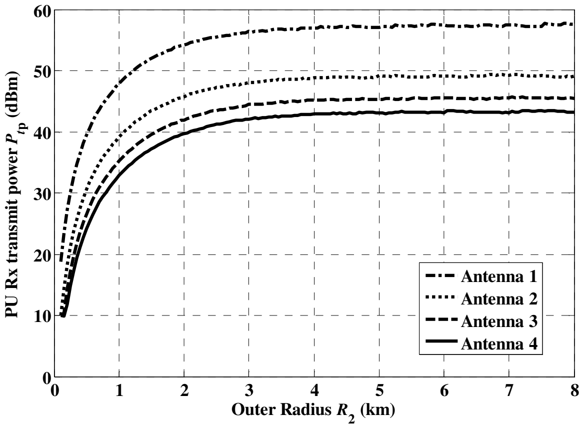

Figure 6. Diversity compensation for required P_{tp} (P = 95%, f_t=1GHz).

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