# PROCESSING SIGNALS OF PASSIVE CHIRP IONOSONDE IN THE PROBLEM OF ESTIMATION THE HF CHANNEL AVAILABILITY

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***Abstract*— The problem of increasing the efficiency of data transmission through a HF radio channel in the case of using passive sounding was studied. The paper presents the main characteristics of the stochastic radio channel with scattering (delay spread, Doppler spread and the signal-to-noise ratio) and communication modem, which have an impact on the efficiency of a communication system. Algorithm for estimating the channel characteristics using passive sounding was developed. Besides, the algorithms aimed at estimating the gain in emitted power and data transfer rate when adapting the communication system to the channel conditions were developed. It was experimentally found that for the mid-latitude radio paths, the power gain is 4.5 ... 12 dB, and the gain in data transfer rate increases up to twice.***

***Keywords*—HF; frequency response function; channel impulse response; power delay profile; signal-to-noise ratio; delay spread; Doppler spread; passive chirp sounder; channel availability**

## I. INTRODUCTION

Short-wave (HF) communication is currently the emergency communication. Satellite communication keeps playing the main role. However, it has the potential to be disrupt by the different factors. It is unstable in polar regions with a latitude of more than 70 degrees; it requires the large financial costs. The problems could be overcome using HF channels for the long distance communication which is cheaper. Thus, we studied the problem of improving the qualitative characteristics of the HF communication using the passive sounding method, which does not require developing the special reception equipment for sounding.

**The aim of the research** is to develop algorithms of passive sounding a HF radio channel, allowing to estimate the channel characteristics and do research of their effectiveness in terms of channel availability as well as estimate the gain in power and data transfer rate using passive sounding over the mid-latitude path Cyprus - Yoshkar-Ola.

## II. MAIN CHARACTERISTICS OF THE RADIO CHANNEL AND MODEMS OF HF COMMUNICATION

The equivalence principle allows to describe the propagation medium of a HF signal as a linear system (radio channel) with m-inputs and one output [1] using the system characteristics: frequency response function (FRF) $H(f,t)=\sum_j H_j(f,t)$ and channel impulse response (CIR) $h(\tau,t)=\sum_j h_j(\tau,t)$. Where, $\tau$ is the "fast" time and $t$ - "slow" time. The scale of changing "fast" time is the range of signal delays. We have assumed that the change in the "slow" time can be neglect at this scale. Random variations of system characteristics are associated with a "slow" time. Thus, averaging over this time is required to obtain statistically stable channel characteristics.

Let us suppose that a random noise with a spectral density $n(f)$ adds to the channel. We have assumed that this noise is white with spectral density $n_0(f)$.

Thus, each path of an equivalent linear system has a FRF $H_j(f,t)$ and CIR $h_j(\tau,t)$, related to each other by the Fourier transform [2], [3]:

$$H(f,t)=H_0\exp[-i\varphi(f,t)]=\sum_{j=1}^{m}H_{0j}(f,t)\exp[-i\varphi_j(f,t)]$$
$$h_j(\tau,t)=\int_{\bar f-B_{ch}/2}^{\bar f+B_{ch}/2}H_{0j}(f,t)\exp[-i\varphi_j(f,t)]\exp[i2\pi f\tau]df \quad ,(1)$$

where $H_0(f,t)$ is the frequency response function of a linear system, $\varphi(f,t)$ - phase response function (PRF) of the system, $H_{0j}(f,t)$ - FRF of the partial path of the equivalent system, $\varphi_j(f,t)$ - PRF of the path, $\bar f$ - central channel frequency, and $B_{ch}$ - channel bandwidth.

The square of the FRF module is called the instantaneous power delay profile (PDP) [4], [5]. Usually the channel is referred to the operating frequency $\bar f$. Thus, for an instantaneous PDP at this frequency, we get the equation (2):

$$\tilde P_\tau(\bar f,\tau,t)=|h(\bar f,\tau,t)|^2 . \quad (2)$$

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The instantaneous PDP is a function of "slow" time which is randomly fading. Averaging over this time allows to obtain a statistically stable estimate, called depending on the sample length either a short-time or a long-time PDP:

$$P_\tau(\bar{f},\tau)=E_t\left[\widetilde{P}_\tau(\bar{f},\tau,t)\right]=E_t\left[\left|h(\bar{f},\tau,t)\right|^2\right], \quad (3)$$

where $E_t[\psi(t)]=\frac{1}{T_a}\int_0^{T_a}\psi(t)\cdot dt$ is the average value of the function over a “slow” time, $T_a$ is the analysis time (sample length) of the function, counted from its start.

The power delay profile allows to estimate the delay in a channel, as well as the delay spread.

Another characteristic associated with “slow” time is the spectrum of CIR fading:

$$s(\bar{f},\tau,F)=\int_{-\infty}^{\infty}h\,(\bar{f},\tau,t)\exp(-j2\pi Ft)dt. \quad (4)$$

The Fourier transform is a method of coherent integration of the subintegral function. Thus, the function

$$S(\bar{f},\tau,F)=\frac{1}{T_a}\left[|\,s(\bar{f},\tau,F)\,|^2\right] \quad (5)$$

called the channel scattering function (CSF) is obtained using the averaging procedure. If we sum (integrate) the CSF values over the “fast” time for each frequency, we will obtain the Doppler power spectrum $P_F(\bar{f},F)$ of CIR.

It allows to estimate the Doppler shift of the frequency for various propagation modes in a channel as well as Doppler spread.

Let us suppose that the CSF has a Gaussian distribution [6]:

$$S(\tau,F_d)=\sum_{j=1}^{M}\left(\frac{S}{N}\right)_j\exp\left[-\frac{(\tau-\tau_{jm})^2}{2\sigma_{j\tau}^2}-\frac{(F_d-F_{jdm})^2}{2\sigma_{jF}^2}\right], \quad (6)$$

where $\tau_{jm}$ is the delay of a random mode in a channel, $F_{jdm}$ - carrier shift in a channel, $\sigma_{j\tau}$ - delay spread in a channel, $\sigma_{jF}$ - Doppler spread, and $\left(\frac{S}{N}\right)_j$ - signal-to-noise ratio equal to the maximum value of the CSF.

The main characteristics which determine the channel conditions are signal-to-noise ratio ($SNR=S/N|_j$), delay spread $\sigma_{j\tau}$, and Doppler spread $\sigma_{jF}$.

Currently, communication modems are mathematically described by the characteristic functions [7], [8]. Their approximation is a rectangular parallelepiped, with sides equal to the limiting channel characteristics [9].

If the point, which marks the channel characteristics, is inside the parallelepiped, then the channel is considered as available. Fig. 1 presents the characteristic function for a given bit error rate (BER) and the point marks the channel characteristics.

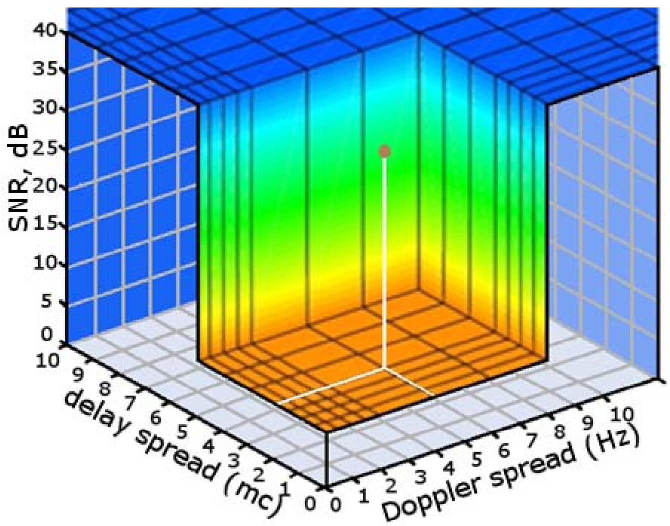


Fig. 1 - Characteristic function. Point marks the channel characteristics [1]

Table I shows the limiting channel characteristics in case of BER = 3, for the modems that use standards: STANAG 4285 [10] [11] [12], STANAG 4539 [9] [10] [11] [12] and MIL-STD-188 -110B [10] [11] [12].

TABLE I. APPROXIMATE VALUES OF SNR, DOPPLER SPREAD AND DELAY SPREAD FOR MODEMS.

| Data rate (baud) | SNR (dB) | Doppler spread (Hz) | Delay spread (ms) |
|---|---|---|---|
| 2400 | >14 | <4 | <5 |
| 1200 | >7 | <8 | <5 |
| 600 | >3 | <12 | <5 |
| 300 | >0 | <16 | <5 |
| 150 | >-3 | <10 | <5 |
| 75 | >-7 | <40 | <16 |

We shall note that with the increasing the data rate, the requirements to the channel characteristics get strict.

Usually, the signal-to-noise ratio changes more rapidly in time than the scattering parameters. Thus, the point which marks the channel characteristics can leave the parallelepiped, and then return back. The use of error correcting codes allows to overcome the problem. For this case, the notion of channel availability is introduce. It is the percentage of times when the point was in the range of permissible channel characteristics.

Usually the channel is considered as available for the certain modem if the point is in the range of permissible channel characteristics of more than 80% of observation time (communication session time).

We have assumed that the SNR parameter has a normal distribution during the observation time with a mean value $\langle SNR\rangle$ and standard deviation $\sigma_{SNR}$. It is clear that the probability of exceeding the value $\eta_m$ will be above 80%, if the inequality (7) is satisfied:

$$\eta_m<\overline{SNR}+\sigma_{SNR}. \quad (7)$$

Thus, equation (7) allows to estimate the channel availability using parameters of the distribution law of the signal-to-noise ratio.

## III. PASSIVE CHIRP SOUNDER AND THE ALGORITHMS FOR ESTIMATING CHANNEL CHARACTERISTICS

Passive sounding system uses signals of chirp sounders. Its distinctive feature is that the signal reception is performed using a receiver with a 3 kHz bandwidth and linear hopping operating frequency. The personal computer is used for signal processing. Synchronization of the receiver is provided by the satellite navigation systems GLONASS and GPS.

Fig. 2 shows the receiving terminal of the passive chirp sounder developed on the Icom-78 communication receiver.

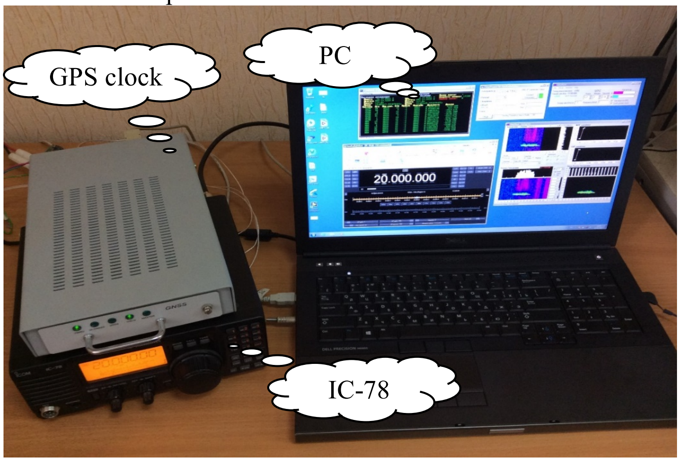


Fig.2 - Receiving terminal of the passive chirp sounder

The signal transferred to zero intermediate frequency with spectrum bandwidth - 0 ... 3 kHz at the output of the receiver can be represent as follows [5]:

$$u_R^{out}(\bar{f}_j,\tilde{t}) = \begin{cases} \sqrt{2P}H_0(\bar{f}_j)\cos\pi\dot{f}(\tilde{t}-\tau_g(\bar{\omega}_i))^2 & \forall\,\tilde{t}\in[0,T] \\ 0 & \forall\,\tilde{t}\notin[0,T] \end{cases} \quad (8)$$

where $\tau_g(\bar{f}_j)$ - signal group delay in a channel, - FRF of a channel.

The sounder uses the matched filter in quadrature signal processing (see Fig. 3).

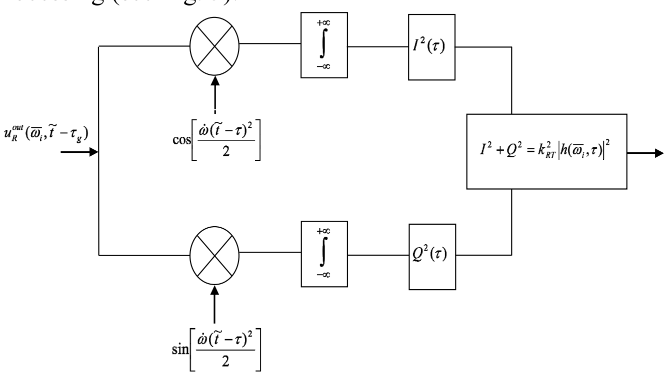


Fig. 3 – Matched filter processing algorithm of a low-frequency sounding signal [5]

As a result, the signal after compression has the form of an instantaneous PDP [5]:

$$\begin{aligned} |U_{RT}(\bar{f}_j,\tau)|^2 &= I^2+Q^2 = k_{RT}^2\left|h(\bar{f}_j,\tau)\right|^2 = \\ &= 2PT^2\cdot H_0^2(\bar{f}_j)\cdot \sin c^2\left(\pi T\dot{f}\left(\tau-\tau_{gj}\right)\right) \end{aligned} \quad (9)$$

The ordered set of power delay profiles represent an ionogram (see Fig. 4a).

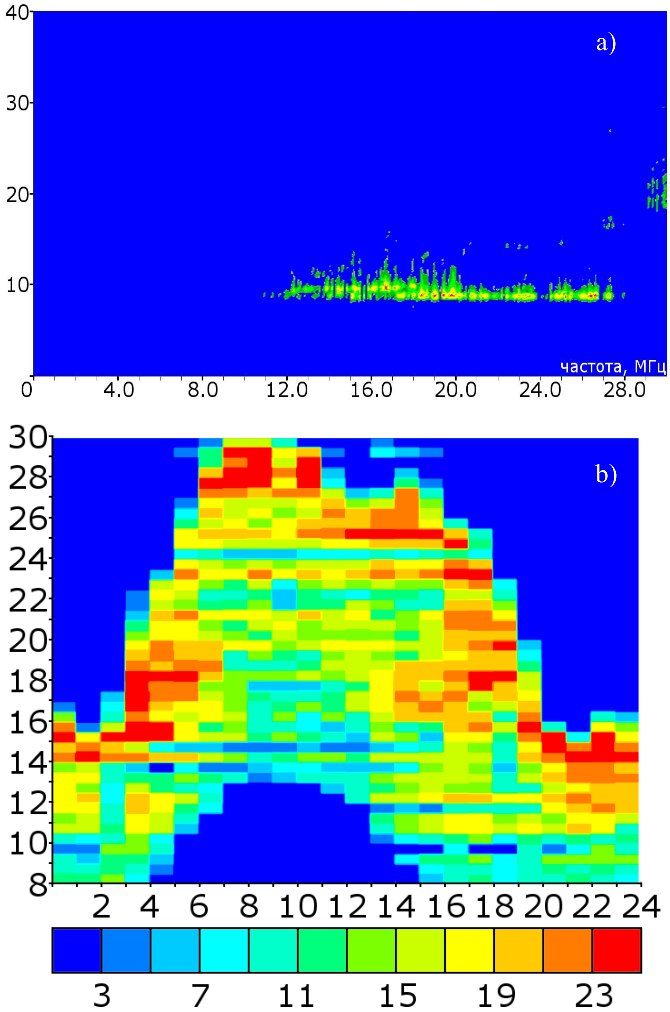


Fig. 4-Ionogram of the Cyprus-Yoshkar-Ola path and the daily variation of frequency dependence of the signal-to-noise ratio

PDP in the digital processing is a set of ordered samples (pixels) by the "fast" time. Some of them contain only noise and the others - signal + noise. The use of threshold processing methods allows to select noise samples and estimate the average noise power during the sounding time - $N$. The maximum value of the signal samples is used to estimate the peak power of the compressed sounding signal. The ratio of maximum value of the signal samples to average noise power is an instantaneous signal-to-noise ratio. Time averaging is required to get a more stable estimation of SNR. We have assumed that the process is ergodic and the scattering parameters close to operating frequencies are weakly varying. In our case, the time averaging performs over the 500 kHz bandwidth. It allows to plot the daily variation of frequency dependence of the averaged SNR (Fig. 4b).

The required power of a communication system transmitter could be estimated if the SNR at the output of the communication system receiver is equal to the SNR at the output of the sounding system. The difference in power is due to the compression of the sounding signal.

We shall note that the noise power does not change after compression due to the lack of correlation between the signal and noise. Let us suppose that for communication system $SNR|_C = L \cdot P_C / N$, and for sounding system $SNR|_s = D \cdot L \cdot P_s / N$ (where $L$ is the losses during propagation). Then, if the SNR of two systems are equal, we get the equation (10):

$$P_c = D \cdot P_s, \tag{10}$$

where $D = B_s \cdot T_s$ - base of the sounding signal, $T_s$ - signal duration at the matched filter input.

In our case, the base of the sounding signal is equal to 73 (approximately 70), because signal bandwidth is 2.7 kHz, and the duration is 27 ms with the frequency sweep rate of 100 kHz/s. Equation (10) allows to recalculate the sounding results for a communication system, which is necessary for using characteristic function in estimations.

Delay spread is estimated using the PDP defined to the -3 dB point. We shall note that the passive chirp sounding method does not allow to determine the Doppler spread. Estimations of Doppler spread are based on the analysis of the papers of A.J. Stocker, E.M. Warrington and D.R. Siddle from the University of Leicester (UK) [11], [12], which present data on the scattering parameters in the frequency and time domains obtained for the period 2002-2003 and 2009 – 2012 from transpolar and mid-latitude radio paths (Fig. 5).

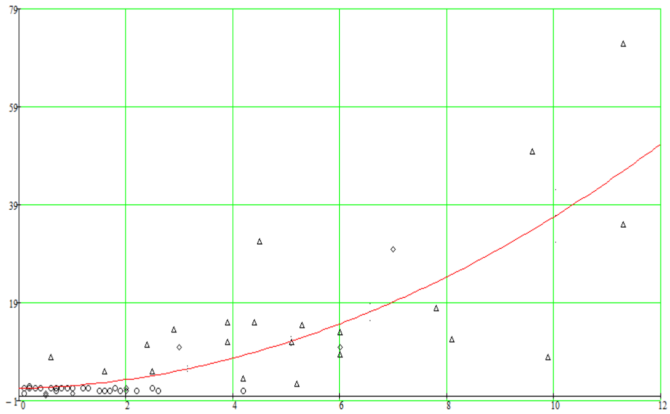

Fig. 5 - Correlation field for estimating the dependence of Doppler spread $\sigma_F$ on delay spread $\sigma_\tau$

The correlated analysis of the field showed a sufficiently high correlation coefficient between changes in the scattering parameters $R(\sigma_\tau, \sigma_{F_d}) = 0.79$. Thus, we suggested a hypothesis of the existence of a regression connection between the parameters according to the parabolic law, and using the least squares method we obtained the equation (11):

$$\sigma_{F_d}[Hz] = f(\sigma_\tau) = K_0 + K_1 \cdot \sigma_\tau[ms] + K_2 \cdot \sigma_\tau^2[ms^2], \tag{11}$$

where $K_0 = 1.55[Hz]$, $K_1 = -0.24[Hz/ms]$, $K_1 = 0.33[Hz/ms^2]$.

Thus, using the developed algorithms and the passive chirp sounder data allows to estimate the availability of HF radio channels for different modems.

## IV. Experimental Estimation of the Passive Sounding Efficiency

We did experimental studies using data obtained from the mid-latitude path Cyprus-Yoshkar-Ola during the period from March 2014 to February 2015. For the analysis, we selected the data of three days for each season. The geomagnetic situation for each selected data was unperturbed. Thus, the selected data are representative.

Based on the results of passive sounding, we studied the effect of the time of day and season on the conditions of two partial channels. We have assumed that the one channel has the maximum possible signal-to-noise ratio and minimum scattering parameters. Its operating frequency we denoted as sounded optimal operating frequency (SOOF). The second channel was formally determined and we have assumed that it corresponds to the operating frequency of 0.85 from the maximum usable frequency (MUF). Its operating frequency we denoted as the formal optimal operating frequency (FOOF). The sounding data were time-averaged over a 500 kHz bandwidth for 1 hour.

The geomagnetic situation was mostly quiet during the observation time. Thus, the scattering data satisfied the parameters of the modems with rates from 75 to 2400 baud. The signal-to-noise ratio was considered as the critical parameter of the channel. At first, we estimated the difference in the parameters of the SNR distribution laws for the channels with the SOOF and FOOF. Table II presents the difference between their SNR average values $\Delta\overline{SNR} = \Delta\overline{SNR}_{SOOF} - \Delta\overline{SNR}_{FOOF}$, and RMS $\Delta\sigma_{\overline{SNR}} = \Delta\sigma_{\Delta\overline{SNR}_{SOOF}} - \Delta\sigma_{\Delta\overline{SNR}\,FOOF}$ for different time of day and different seasons.

TABLE II. The difference between the parameters of the distribution laws of the SOOF and FOOF.

| | Night | | Morning | |
|---|---|---|---|---|
| | $\Delta\overline{SNR}$ | $\Delta\sigma_{\overline{SNR}}$ | $\Delta\overline{SNR}$ | $\Delta\sigma_{\overline{SNR}}$ |
| Spring | 4,1 | 1,6 | 3,3 | 3,3 |
| Summer | 1,7 | 2,1 | 3,3 | 3,5 |
| Autumn | 3,1 | 2,8 | 11,8 | 6,0 |
| Winter | 2,6 | 2,7 | 8,5 | 7,3 |
| | Day | | Evening | |
| | $\Delta\overline{SNR}$ | $\Delta\sigma_{\overline{SNR}}$ | $\Delta\overline{SNR}$ | $\Delta\sigma_{\overline{SNR}}$ |
| Spring | 6,8 | 1,5 | 4,4 | 2,6 |
| Summer | 0,7 | 1,0 | 1,9 | 2,8 |
| Autumn | 8,5 | 2,2 | 8,0 | 5,4 |
| Winter | 5,8 | 2,4 | 4,2 | 3,7 |

Table III presents the gain caused by the use of the passive chirp sounder with 80% channel availability.

TABLE III. THE GAIN IN SNR CAUSED BY USING THE PASSIVE CHIRP SOUNDING.

| | **Average seasonal difference** | | **Gain** |
|---|---|---|---|
| | $\Delta SNR$ | $\Delta \sigma_{SNR}$ | $\Delta SNR_{MAX} + \Delta \sigma_{SNR}$ |
| Spring | 4,7 | 2,3 | 7,0 |
| Summer | 1,9 | 2,4 | 4,3 |
| Autumn | 7,9 | 4,1 | 12 |
| Winter | 5,3 | 4,0 | 9,3 |

Thus, the gain in the signal-to-noise ratio for the communication system, and, consequently, the gain in the emitted power is 4.5-12 dB.

The obtained data allows to estimate the possible data transfer rates for the channels with the equal transmitter power. Table 4 presents the estimates of the average data rate in the channels for the transmitter power of 10 dBW, 20 dBW and 30 dBW.

TABLE IV. THE AVERAGE DATA RATE ON SOOF AND FOOF.

| | **Transmitter power, dBW** | | **Average data rate, baud** | **Data rate defined by the standard STANAG 4539, baud** |
|---|---|---|---|---|
| Spring | 10 | FOOF | 188,3 | 150 |
| | | SOOF | 399 | 300 |
| | 20 | FOOF | 800,8 | 600 |
| | | SOOF | 1208,3 | 1200 |
| | 30 | FOOF | 1896,8 | 1200 |
| | | SOOF | 2400 | 2400 |
| Summer | 10 | FOOF | 425,8 | 300 |
| | | SOOF | 508,3 | 300 |
| | 20 | FOOF | 1161,9 | 600 |
| | | SOOF | 1350 | 1200 |
| | 30 | FOOF | 1947.7 | 1200 |
| | | SOOF | 2400 | 2400 |
| Autumn | 10 | FOOF | 305,1 | 300 |
| | | SOOF | 456,5 | 300 |
| | 20 | FOOF | 947,9 | 600 |
| | | SOOF | 1210,4 | 1200 |
| | 30 | FOOF | 1634 | 1200 |
| | | SOOF | 1950 | 1200 |
| Winter | 10 | FOOF | 293,5 | 150 |
| | | SOOF | 469,8 | 300 |
| | 20 | FOOF | 1076,3 | 600 |
| | | SOOF | 1425 | 1200 |
| | 30 | FOOF | 1810 | 1200 |
| | | SOOF | 2400 | 2400 |

The outcome of the data presented in the table is that the use of passive sounding allows to increase the data transfer rate up to twice.

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