Dynamic Optical Code Division Multiple Access Communication System Analysis and Performance Enhancement by Signal Clipping

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***Abstract*—Dynamic optical code division multiple access (DOCDMA) communication system is proposed. In a DOCDMA system, the central wavelength of electrically controlled tunable optical filter (TOF) at the transmitter is dynamically varied during the bit period according to a functional code. An enhancement of the system is also proposed by clipping the signal at the decoder of each receiver. The system is modeled and analyzed with and without signal clipping taking into account the multiple access interference, thermal noise, and phase induced intensity noise. The performance of the enhanced system is compared with that of a DOCDMA system without signal clipping, fast frequency hopping, and with a spectral amplitude coding system that uses either a Hadamard code, a modified quadratic congruence code, or modified frequency hopping code. The results show that the proposed system improve the bit error rate performance. Signal clipping method reduces the multiple access interference and improve the bit error rate performance of the system.**

***Index Terms*—Multiple access interference, optical code division multiple access (CDMA), optical fiber communication.**

I. INTRODUCTION

Early optical CDMA systems coded the incoherent pulses in time domain and recovered the data at the receiver using taped delay lines. The performance of these systems is poor because of the correlation properties of the special unipolar codes used and the summation required [1]. A more recent technique for optical CDMA systems uses spectral amplitude coding (SAC). In these systems, the spectrum of a broadband source is encoded. Further, the multiple access interference can be canceled in these systems by using code sequences with fixed in-phase cross correlation [2]. However, the phase induced intensity noise (PIIN) is the main parameter that limits the performance of this type of systems [3]. Optical fast frequency hopping CDMA (FFH) system was proposed in the late 1990's and it utilizes both time and frequency domains for encoding the optical signal [4]. Frequency separation between successive chip pulses is required in FFH system to reduce the side lobe effects of the gratings. This limits the maximum number of users in the system. Furthermore, the spatial distance between the gratings and the number of gratings limits the users data bit rate in the system.

In this letter we propose a dynamic optical CDMA (DOCDMA) system with signal clipping. The encoder varies the central frequency of the pulse optical signal according to a functional code. The synchronized system can recover the encoded data by a matched tunable optical filter at the receiver. DOCDMA signals interfere only during the time of intersection between the functional codes driving the TOF's. It has been found that the PIIN is effectively suppressed using this system and the main noise source for this system is the multiple access interference (MAI). The system performance is better compared to the FFH and SAC systems recently proposed [4],[5]. Clipping the signal at the output of the detector reduces the effect of the MAI on the system and improves the performance. This scheme uses codes based on wavelength modulation implemented with a synchronized fast TOF in each encoder and decoder. The small data bit period interval of the high data bit rate system requires a special code with scanning range suitable with the speed of the TOF. However, tunable optical filters which can scan 10's of nano-meters within few ns have been reported [6]. The encoder and decoder can be easily reconfigured to any of the functional codes without the need for any hardware modification.

II. SYSTEM CONFIGURATION AND DESCRIPTION

The block diagram in Fig. 1(a) shows the DOCDMA configuration. The broadband signal from the light source is OOK modulated with the binary data. For each data bit of "1", encoder $j, j \in \{1,2,...K\}$, where K is the number of simultaneous users, will filter the spectrum of the pulse at a central wavelength which varies according to a functional code $F^j(t)$. The encoder is simply a tunable optical filter controlled with an electrical signal which represents the functional code. Signals transmitted from all synchronized

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users will be combined using a start coupler before received by all users. At the receiver, the composite signal is decoded by a matched tunable optical filter. Then, the signal passes through a photodetector, an integrator, and a threshold decision to recover the data transmitted.

The source spectra are assumed to be flat over the bandwidth of $\upsilon_0 \pm \Delta\upsilon/2$, with magnitude $P_r/\Delta\upsilon$, where υ_0 is the central optical frequency, $\Delta\upsilon$ is the system bandwidth, and P_r is the received effective average power from a single source. Any excess losses in the route of the signal and the receiver are assumed to be incorporated in P_r. Ideal masking at the tunable optical filter is also assumed, and each user is considered to have the same effective average power at each receiver. The transmitter sends a pulse with spectral distribution varying with time if the data bit value is "1"; otherwise no power is transmitted. Fig. 1(b) shows the spectrum of j^{th} user's transmitted signal when the data bit is "1". The spectrum is similar to that of an ideal filter with central frequency varying with time according to a functional code. The proposed functional codes family $F(t)$ is sine functions family with the same frequency and different phase shifts. Fig. 1(c) shows an example of the spectrum for two users at the input of the decoder during one bit period when both users are sending a bit of "1". At the receiver side, the TOFs of the decoders are synchronized in time with a phase shift related to the functional code for each one of them. The output of the decoder is therefore the original signal which has the same phase shift of the decoder with some interference noise at the points of intersection with other users. Small portion of the bandwidth can be used to control the synchronization or any other method, but Synchronous transmission implementation is not considered in this letter.

III. CODE CONSTRUCTION

The main criterion in the functional codes construction is to minimize the number of intersecting points between any pair of functions since they increase the interfering power between users. The area of intersection between any two functions which is related directly to the value of interfering power is also an important parameter in the construction of the functional codes. In our proposal, we suggest the use of shifted sine functions to alter the optical central frequency (υ_0) for coding the transmitted signal. The code family is given by,

$$F^j(t) = \frac{\Delta\upsilon}{2}\sin(2\pi f t - j\varphi) \quad (1)$$

where f is the frequency of the functional code, and φ is the phase shift between different functions. Sine shifted functions are proposed for their simplicity to prove the concept and the ease of achieving the large number of codes required by reducing the phase shift. The speed of the TOF and its controller required is directly proportional to the frequency of the functional code f. The code construction is limited by the speed of the tunable optical filter because it determines the frequency range and the speed that the TOF required to span during the data bit interval. Furthermore, the functional codes proposed start and stop at the same central wavelength during the bit period T for smooth modulation of the TOF and its controller. For these two reasons the choice was to use a frequency equals to the data bit rate. Phase shift is chosen taking into consideration the spacing between users and the code cardinality. Smaller phase shift results in larger number of codes since the code will repeat it self after 2π radians. Reducing the phase shift will bring the users closer to each other in the spectrum. The phase shift is chosen to be $2\pi/170$, that's will give a maximum number of different codes of 170 which is close to the cardinality of the family of MQC code with $p = 13$ proposed in [2] and [3].

For this type of CDMA system, fast TOF will do the whole encoding and decoding by modulating the central wavelength of the filter during the bit period. One of the important features of the optical filter is the speed of tuning which is the key parameter for this application. Nanosecond tunable optical filters are available from microresonators, electrooptic, and active distributed Bragg reflector technologies [6]. The TOF in Dynamic Optical CDMA should be able to follow the functional code driving the filter. Other codes might be proposed to improve the system performance and relaxes the implementation of the system for high data bit rates.

IV. DOCDMA PERFORMANCE ANALYSIS

In the analysis of BER we consider the effect of MAI, PIIN, and the thermal noise. Other sources, like shot noise and receiver's dark current noise are neglected and Gaussian approximation is used for the calculation of the BER.

The variance of photocurrent detected from unpolarized thermal light source generated by spontaneous emission including the effect of MAI can be expressed as,

$$\langle i^2 \rangle = (K-1)\sigma^2 + I^2 B\tau_c + 4K_b T_n B / R_L \quad (2)$$

where σ^2 is the variance of the MAI, I is the average photocurrent, B is the noise-equivalent electrical bandwidth of the receiver, τ_c is the coherence time, K_b is the Boltzmann's constant, T_n is the absolute receiver noise temperature, and R_L is the receiver load resistor. The first term of this equation represent the MAI effect, the second term denotes the effect of PIIN where incoherent light sources mixed at the input of the photodetector will cause intensity variations of the output current, and the third term represents the effect of thermal noise.

The power spectral density (PSD) $G(\upsilon,t)$ of the signal at the input of receiver m, $m \in \{1,2,...K\}$ is the sum of all active users' transmitted signals,

$$G_{im}(\upsilon,t)=\frac{P_r}{\Delta\upsilon}\sum_{j=1}^{K}b^j rect\left(\frac{\upsilon-\upsilon_0-F^j(t)}{BW}\right) \tag{3}$$

where $rect\left(\frac{\upsilon-\upsilon_0}{BW}\right)=u\left(\upsilon-\upsilon_0+\frac{BW}{2}\right)-u\left(\upsilon-\upsilon_0-\frac{BW}{2}\right)$, $u(\upsilon)$ is the unit step function, BW is the Bandwidth of the TOF's, and b^j is the data bit value of user j.

The receiver applies a synchronized matched filter (decoding) to the incoming signal to extract the desired users' bit stream. The decoder output is,

$$G_{om}(\upsilon,t)=\frac{P_r}{\Delta\upsilon}b^m rect\left(\frac{\upsilon-\upsilon_0-F^m(t)}{BW}\right)+ \\ \left(\frac{P_r}{\Delta\upsilon}\sum_{j=1,j\neq m}^{K}b^j rect\left(\frac{\upsilon-\upsilon_0-F^j(t)}{BW}\right)\right)rect\left(\frac{\upsilon-\upsilon_0-F^m(t)}{BW}\right) \tag{4}$$

Then, the photocurrent is,

$$I_m(t)=\Re\int_{v=0}^{\infty}G_{om}(\upsilon,t)d\upsilon=\Re\frac{P_r}{\Delta\upsilon}b^m BW+\Re\frac{P_r}{\Delta\upsilon}\sum_{j=1,j\neq m}^{K}b^j \\ \sum_{i=1}^{N_{m,j}}\left(BW-\left|F^m(t)-F^j(t)\right|\right)\left(u\left(t-\tau L_i^{m,j}\right)-u\left(t-\tau H_i^{m,j}\right)\right) \tag{5}$$

where $\Re=\frac{\eta e}{h\upsilon_0}$ is the responsivity of the photodetector, here η is quantum efficiency, e is the electron's charge, h is Blank's constant, $N_{m,j}$ is the number of intersecting points between users m, and j during one bit period, and $\tau L_i^{m,j}$,$\tau H_i^{m,j}$ defined as the roots of the following equations respectively,

$$F^m(t)-F^j(t)-BW=0 \\ F^m(t)-F^j(t)+BW=0 \tag{6}$$

After the integrator and sampler, the optical photocurrent is:

$$I_m=\frac{1}{T}\int_{t=0}^{T}I_m(t)dt=\Re b^m\frac{P_r}{\Delta\upsilon}BW+\Re\frac{P_r}{T\Delta\upsilon}\sum_{j=1,j\neq m}^{K}b^j \\ \sum_{i=1}^{N_{m,j}}\left(BW(\tau H_i^{m,j}-\tau L_i^{m,j})-\int_{L_i^{m,j}}^{\tau H_i^{m,j}}\left|F^j(t)-F^m(t)\right|dt\right) \tag{7}$$

The optical photocurrent at the receiver of user m $m\in\{1,2,\ldots K\}$ after the integrator and sampler can be reformulated as:

$$I_m=b^m I+MAI(m) \tag{8}$$

where $I=\Re\frac{P_r}{\Delta\upsilon}BW$, and the multiple access interference at receiver m, $MAI(m)$ is given by,

$$MAI(m)=\sum_{j=0,j\neq m}^{K}DAI(m,j) \tag{9}$$

where,

$$DAI(m,j)=\Re\frac{P_r}{T\Delta\upsilon} \\ \sum_{i=1}^{N_{m,j}}\left(BW\left(\tau H_i^{m,j}-\tau L_i^{m,j}\right)-\int_{\tau L_i^{m,j}}^{\tau H_i^{m,j}}\left|F^j(t)-F^m(t)\right|dt\right) \tag{10}$$

is the interference between users m and j,

In equation (8), the first term is the data bit of the desired user *m*, and the second term is the MAI Noise.

Since our system is synchronized, users *m* and *j* will interfere at the same points in time relative to the beginning of the bit period, and the intersecting edges $\tau L^{m,j}_i$ and $\tau H^{m,j}_i$ are the same whenever users *m* and *j* are active. This results in a constant value of $DAI(m,j)$ if users *m* and *j* are active, otherwise $DAI(m,j)$ is zero. For equi-probable data, $DAI(m,j)$ is random variable with average and variance given in (11) and (12) respectively,

$$\mu_{DAI}=\frac{1}{K^2-K}\sum_{m=1}^{K}\sum_{j=1,j\neq m}^{K}DAI(m,j) \tag{11}$$

$$\sigma^2=\frac{1}{K^2-K}\sum_{m=1}^{K}\sum_{j=1,j\neq m}^{K}\left(DAI(m,j)-\mu_{DAI}\right)^2 \tag{12}$$

The variance of MAI can be approximated as $(k-1)\sigma^2$ for *k* simultaneous active users. To improve the performance of the system, clipping the signal is used after the decoder in each receiver as shown in Fig. 1(a). The clipper is an optical hard limiter which is used in DS-OCDMA system and it is defined as [1],

$$H(x)=\begin{cases}1 & x\geq 1\\ 0 & 0\leq x<1\end{cases}, \tag{13}$$

When using the signal clipper, the photocurrent is defined as,

$$I_m(t)=\Re\int_{v=0}^{\infty}H\left(G_{om}(\upsilon,t)\right)d\upsilon=\Re\frac{P_r}{\Delta\upsilon}b^m BW+\overline{b_m}\Re\frac{P_r}{\Delta\upsilon} \\ \sum_{j=1,j\neq m}^{K}b^j\sum_{i=1}^{N_{m,j}}\begin{cases}BW & if\ \left(BW-\left|F^m(t)-F^j(t)\right|\right)\left(u\left(t-\tau L_i^{m,j}\right)-u\left(t-\tau H_i^{m,j}\right)\right)\geq BW\\ 0 & Otherwise\end{cases} \tag{14}$$

The new random variable (DAIC) of the interference between two users is now defined as the integration of the second term in equation (14) excluding the summation over j,

$$DAIC(m,j)=\overline{b_m}\Re\frac{P_r}{\Delta\upsilon}\int_{\tau L_i^{m,j}}^{\tau H_i^{m,j}}\left(\sum_{i=1}^{N_{m,j}}\begin{matrix} BW & if\ \left(BW-\left|F^m(t)-F^j(t)\right|\right) \\ & \left(u\left(t-\tau L_i^{m,j}\right)-u\left(t-\tau H_i^{m,j}\right)\right)\geq BW \\ 0 & Otherwise\end{matrix}\right)dt \tag{15}$$

Similar equations to (11) and (12) are used to find the average and variance of the interference random variable in a system using clipping method.

The variance of the PIIN is related to the coherence time of the source which is given by,

$$\tau_c(t)=\left(\int_{v=0}^{\infty}G_m^2(\upsilon,t)d\upsilon\right)\Bigg/\left(\int_{v=0}^{\infty}G_m(\upsilon,t)d\upsilon\right)^2 \tag{16}$$

The variance of the PIIN causes variations in the output current during interference of incoherent light sources at the input of photodetector. Assuming no more than one pair of users interfering at the same time which is the case as in our proposed functional code family and averaging the variance at the points of interference along the bit period and averaging over all users, the PIIN variance equation for equiprobable data can be given by,

$$\sigma_{PIIN}^2=\frac{1}{2K}\sum_{m=1}^{K}\frac{1}{T}\int_0^T B\Re^2\sum_{j=1,j\neq m}^{K}\sum_{i=1}^{N_{m,j}}\left(\left(\frac{P_r}{\Delta\upsilon}b_m+\frac{P_r}{\Delta\upsilon}b_j\right)^2\left(BW-\left|F^m(t)-F^j(t)\right|\right)+\left(\frac{P_r}{\Delta\upsilon}b\right)^2\left|F^m(t)-F^j(t)\right|\right)\left(u\left(t-\tau L_i^{m,j}\right)-u\left(t-\tau H_i^{m,j}\right)\right)dt \tag{17}$$

The signal to noise ratio can be expressed as

$$SNR(K)=\frac{I^2}{(K-1)\sigma^2+\sigma_{PIIN}^2+\dfrac{4K_bT_nB}{R_l}}, \tag{18}$$

and using Gaussian approximation, the BER is given by

$$BER=\frac{1}{2}erfc\left(\sqrt{\frac{SNR}{2}}\right) \tag{19}$$

The BER performance of DOCDMA using sine functional code family proposed and another two optical CDMA systems, one is FFH-OCDMA system and the other is SAC using either Hadamard code, MQC code with prime number of 13 [3], or MFH code with q=16, are plotted in Fig. 2 for the sake of comparison. It shows the relation between the BER and the number of simultaneous active users when $P_r=-10dBm$. In our calculations we take $\Delta\upsilon=30\,nm$, $\upsilon_0=1550\,nm$, $BR=155\,Mbps$, and filter bandwidth of $BW=0.165\,nm$ which is equal to the chip width of SAC system using MQC with $p=13$ and same optical bandwidth. For an error rate of 10^{-11}, DOCDMA can accommodate up to 80 users without clipping, whereas for other systems, the maximum simultaneous users are 32 for SAC system using Hadamard code, 52 for SAC system using MQC code, 58 for SAC system using MFH code, and 24 for FFH system. The BER of the DOCDMA system is increasing at a slower rate than that of the other two systems, which indicates that there is a significant improvement in performance at large number of users. Indeed it is shown that the BER for DOCDMA is better that any other system at any number of users of more than 50. However, for less than 50 active users, SAC system with MFH or MQC gives BER better than that of DOCDMA system. It should be noted that for this range of users, the error rate is too small (less than 10^{-14}). Clipping the signal at the receiver enhances the BER performance of the system. System with signal clipping can accommodate 160 users with a BER less than 10^{-13} since the major effect coming from the MAI is reduced.

V. CONCLUSION

We have proposed a novel low noise dynamic optical CDMA communication system. The encoder/decoder design is based on fast tunable optical filter. The filters are controlled dynamically and moves one cycle during the data bit period. The system is analyzed with a simple sine shifted functional code family taking into account the multiple access interference, the thermal noise, and the phase induced intensity noise. The system shows very small BER at large number of simultaneous active users compared with other systems like SAC-CDMA and fast frequency hopping systems. Although in the proposed system, the data transmission rate is limited by the tunable filter's tuning speed, other functional code families can be used whereby the requirement for tuning speed can be reduced so that the system can support higher bit rates. We enhance the performance of the system by using signal clipping ant the receiver. The system shows an improved BER when the signal clipping is used because the interference effect on the performance of the system is reduced by clipping the signal at the output of the decoder.

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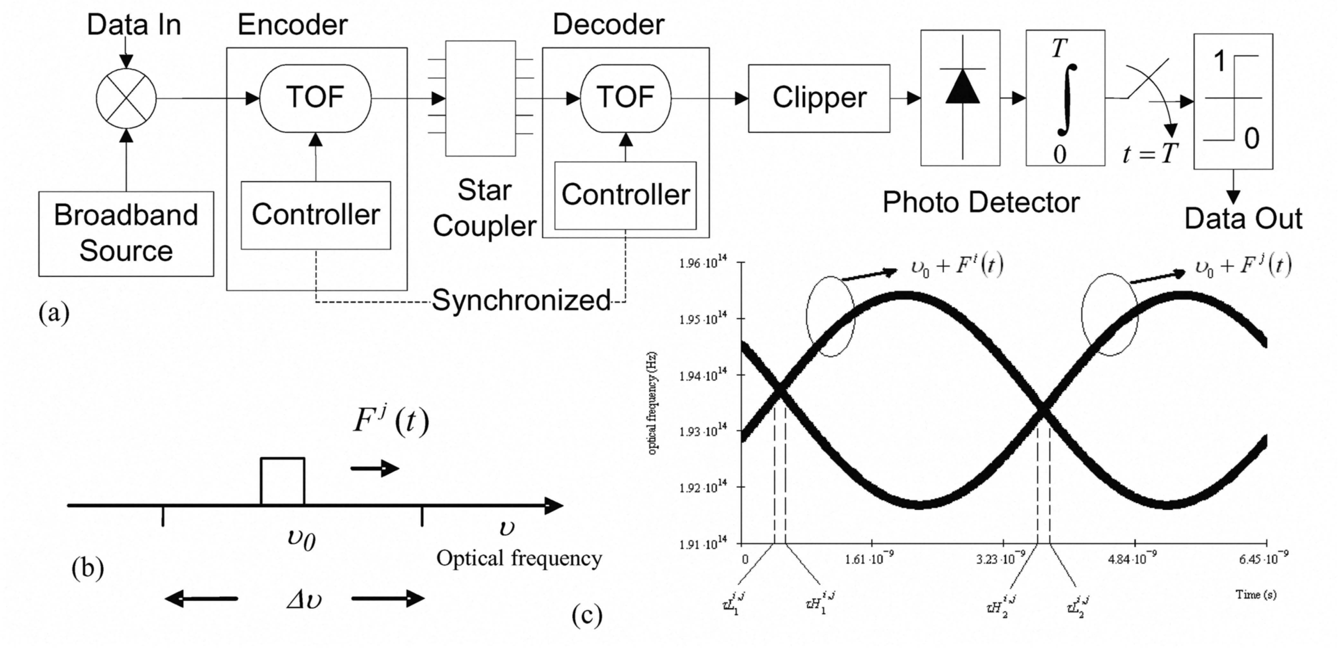

Fig. 1. (a) Block diagram of Dynamic OCDMA system. (b) Optical spectrum of a signal from one of the users. (c) Power spectral density for two users as a function of time and frequency.

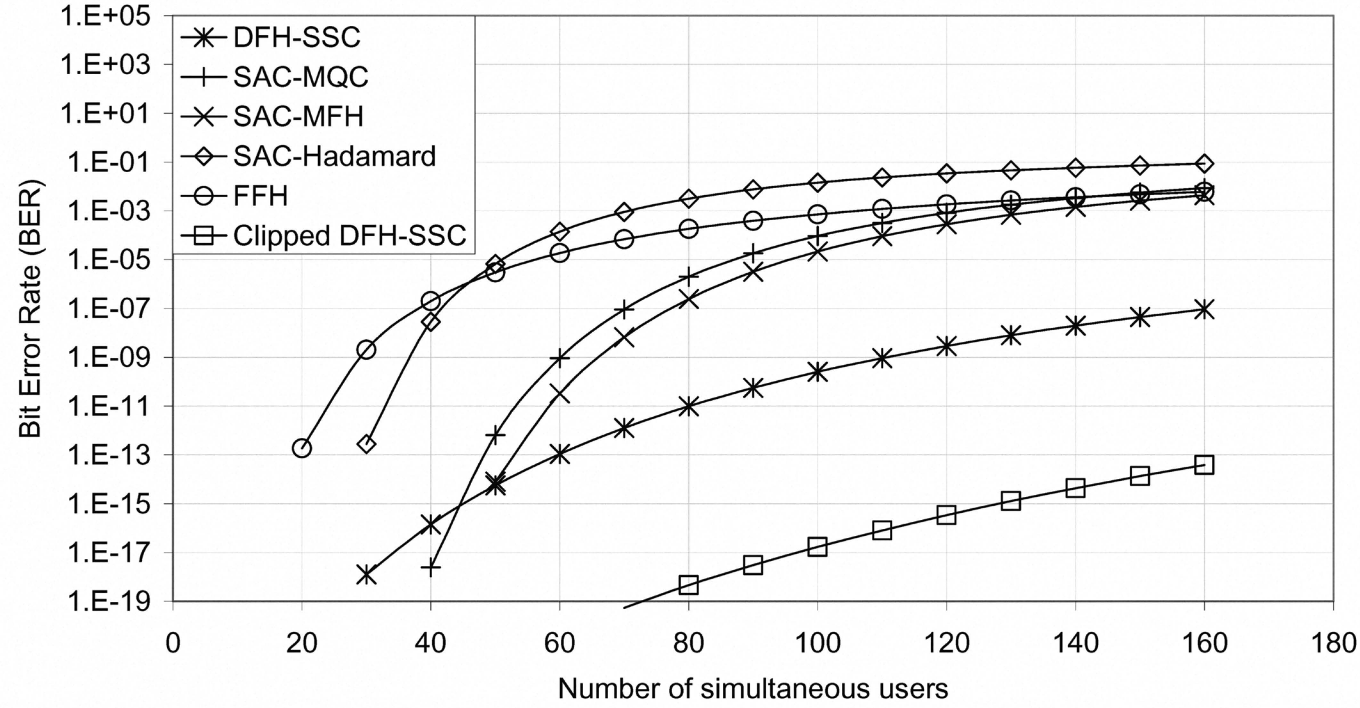

Fig. 2. Comparison of DOCDMA system probability of error with other OCMDA systems when $P_r = -10$ dBm