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Procedia Technology 6 (2012) 723 – 730
Procedia Technology

2nd International Conference on Communication, Computing and Security [ICCCS-2012]

Optimized Hybrid Optical Communication System for First Mile and Last Mile Problem Solution of Today's Optical Network

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Abstract

We have proposed an optimized hybrid optical communication system for bit-rates of 160Gbps/ channel, 100Gbps/channel and 40Gbps/channel. The system composed of 8-channel dense wavelength division multiplexing (DWDM) fiber optic link for long-haul, and wireless optical diffused link for short-haul, multicasting applications. The use of wireless optical diffused links at either end, solve the today's first mile and last mile problem of optical communication network. The wireless optical diffused link uses the optimized coherent optical quadrature phase shift keying modulation technique, as it offers the best performance in the presence of atmospheric turbulence effect. However, the fiber based DWDM system uses symmetrical dispersion compensation technique, with optimized modified duo-binary return-to-zero modulation format as it performs the best, in the presence of fiber non-linearity and dispersion. The system operates with the centre frequency of 193.1THz. The system performance is analyzed in terms of quality-factor, bit error rate, eye opening etc. For the bit rate of 160Gbps, the optimized coverage distance found is 126m of wireless optical diffused link and 450km of fiber optic link. The proposed system will be highly useful for present and next generation long distance optical communication systems and computer networks.

Keywords: Fiber and free-space hybrid optical (FFHO) network; Modified duo-binary return-to-zero (MDRZ); coherent optical quadrature phase shift keying (QPSK) technique; quality (Q)-factor; bit error rate (BER).

1. Introduction

At the present scenario the "first mile" and "last mile" access remain an unsolved problem for the world's telecommunications carriers, despite many attempts at solving the problem. Unlicensed wireless radio frequency (RF) technologies can be used but are limited in capacity, and carriers are reluctant to install in systems that might have interference issues. Licensed wireless RF technologies can provide very high capacity, but the nonrecurring initial capital expenditures for spectrum licenses usually make the business model very difficult to implement. Again, in any given city the licenses permit only two carriers to participate [1, 2]. Each of the current network technologies, such as

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doi:10.1016/j.protcy.2012.10.087

coaxial wire, twisted pair, microwave radio link; wireless (fixed / mobile) and optical fiber provide different levels of mobility and specific bandwidth to each user. The major challenging task with these systems is the feasibility of cost and implementation. Recent trends reflect the continuous increase in the demand of broadband (such as "Quad-play," which refers to voice, video, internet and wireless) and mobile communications with continuous connectivity and high quality standards, pose a challenge on the network technologies. The current networks, either wired or wireless, satisfy just a part of the new demands due to some of inherent bottlenecks of the used technologies.

Thus taking into the account of growing requirements and separately the advantages and disadvantages of the existing techniques, there comes the necessity of the implementation of a hybrid network, in which the limitations of one technology can be overcome via the coexistence of another technology, in the same network [1]. The proposed hybrid optical communication system is a promising architecture for future access networks. Here, the fiber need not to penetrate end user; hence it extends the reach of emerging optical-access solutions, such as passive optical networks (PON).

Sheetal et. al designed a long-haul fiber optic DWDM communication system of 40Gbps bit-rate during the year 2010 and they proved that among all modulation formats modified duo-binary return-to-zero (MDRZ) is the best, for tolerating dispersion and non-linearity present in the optical fiber [3]. They also proved that among several dispersion compensation techniques, symmetric dispersion compensation technique is the best for DWDM system.

For the diffused link (DL) setup, though the intensity modulation technique is extensively used because of its simplicity, it does not offer immunity to the turbulence induced fading channels [4]. The non-predictive behavior of turbulence level produces random fluctuation of the optical intensity level, at the receiver. Thus, an adaptive thresholding for optimal performance is required. Because of implementation complexity adaptive thresholding is practically not suitable. As the optical intensity level is get affected by scintillation affects, it is a reasonable approach to use modulation techniques that carries the information in the phase or frequency of the carrier signal. For phase shift keying (PSK) based modulation technique, adaptive thresholding scheme is not required, hence offers superior performance compared to the intensity modulation technique in the presence of the atmospheric turbulence induced fading channels [5]. Among several PSK techniques coherent optical quadrature phase shift keying (QPSK) is proved to be the best for DL setup, as it is spectrally efficient with low probability of error and higher coverage distance [6]. Hence, coherent optical QPSK modulation technique is proposed here for DL setup.

Aburakawa et al. designed a fiber free-space hybrid optical (FFHO) network and they proved that this technique is very much helpful for new generation mobile access network [7]. Similarly Leitgeb et al. designed free-space optics system, an extension to fiber networks and they proved that the technique is helpful for last mile solution [8]. For point to point communication, fiber optic link is suitable but not for multicasting purpose. At the same time the DL setup or non-line-of sight setup is suitable for multicasting purpose but suffers from severe attenuation and atmospheric turbulence. Hence, DL systems are not suitable for long-haul communication but used for multicasting purpose. Considering the advantage and disadvantage of each system, here a hybrid optical communication system is designed and simulated, which is a combination of fiber link and wireless optical DL setup and provides a possible solution for solving first mile and last mile solution. As per authors' knowledge such a hybrid communication system with higher bit-rate is designed for the first time. It will be highly helpful for systems, where the front and back end of the system will be a short-haul free-space DL setup and in between a long haul fiber DWDM setup is placed (Ex: - Hybrid wireless-optical broadband-access network (WOBAN), Pico-cellular mobile systems etc) [1, 3].

2. Coherent optical quadrature phase shift keying (QPSK) technique

Fig. 1 shows the block diagram of coherent optical QPSK transmitter [9]. Here, the number of bits per symbol considered is 2. The transmitter consists of PSK sequence generator, which generates the in-phase (I) and quadrature signals (Q) as given in equation (1) and (2) respectively. Table 1 gives the details of I and Q signal as per the incoming symbol. The output of the PSK sequence generator is given to the M-array pulse generator, where M =4. The optical signal is fed to the Mach-Zehnder modulator (MZM) using a coupler and finally the I and Q signal is combined using an optical power combiner as shown in Fig. 1. The I and Q signal is given by [9],

$$I_i = \cos(\theta_i) \tag{1}$$

$$Q_i = \sin(\theta_i) \tag{2}$$

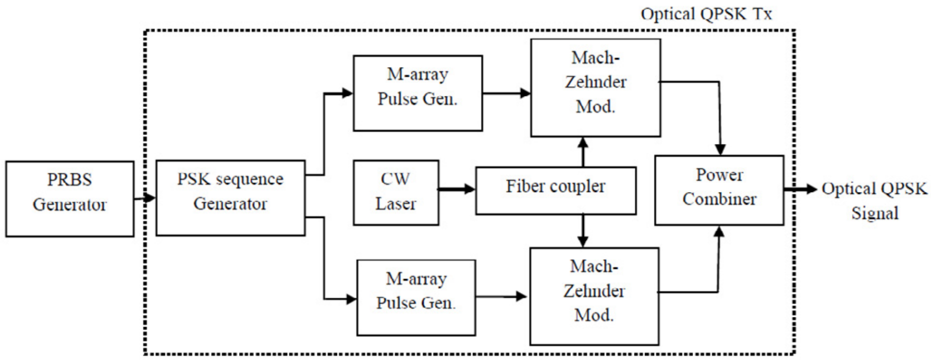

Fig. 1. Block diagram of coherent optical QPSK transmitter

where $\theta_i = 2\pi(i-1)/M$, $\forall i = 1,2,3,4$ and $M = 4$.

3. Modified duo-binary return to zero (MDRZ) modulation format

MDRZ is generated by first creating an non-return to zero (NRZ) duo-binary signal using a delay-and-substractor circuit. Then it drives the first MZM and concatenating this modulator with a second modulator that is driven by a sinusoidal electrical signal with the frequency of half the bit-rate and a phase of -90^0. In MDRZ the carrier of duo-binary signal has been suppressed [3].

4. Free-space optical diffused link (DL) setup

Free-space diffused link setup is used for multicasting purpose, thus used for the solution of last mile and first mile problem. It can provide virtually unlimited bandwidth at a relatively high performance and low cost communication over short distances up to a few hundred meters [10,11]. In addition, DL links do not require any spectrum allocation by the Federal Communications Commission (FCC). These links are also rapidly deployable, scalable and flexible. Here QPSK modulation with optical carrier signal frequency of 193.1THz is used for higher coverage distance with less probability of error in the presence of atmospheric turbulence [12, 13]. For the DL set up, the received power at a distance of R (km) from the transmitter is given by [14],

$$P_R = P_T \frac{d_R^2}{(d_T + \theta R)^2} 10^{\frac{-\alpha R}{10}} \tag{3}$$

where:
P_R: Received Power, P_T: Transmitted Power, d_R: Receiver aperture diameter (m), d_T: Transmitter aperture diameter (m), θ: Beam divergence (mrad), R: Range(km), α: Atmospheric attenuation in dB/km

5. Fiber based dense wavelength division multiplexing (DWDM) setup

To make full use of huge bandwidth resources of SSMF, DWDM technology is used. High spectral efficiency in DWDM system can be achieved with an attractive bit rate of $\geq$ 10Gbps [10]. To achieve transmission over an appreciable distance, dispersion and nonlinearity must be managed properly. Dispersion management, using specialized fiber of opposite direction values, is a key technique that maintains the total accumulated dispersion low, while suppressing the nonlinear effects. In dispersion-managed systems, using SSMF and dispersion compensating fiber (DCF), the positive dispersion of SSMF can be compensated by large negative dispersion of DCF [3]. Hence, the overall dispersion accumulation is minimized over a fairly wide wavelength range and the non linear effect such as four-wave mixing (FWM) is also significantly reduced [3, 9].

6. Proposed hybrid optical communication system

The block diagram of the proposed hybrid optical communication system is shown in Fig.2. The front end and back end of the setup consists of eight number of DL setups for multicasting purpose and to solve the first mile and last mile problem respectively. Each DL setup consists of a transmitter, the free-space channel and a receiver [10]. Transmitter consists of a pseudo random bit sequence generator (PRBS), which generates the random data bits (0s and 1s) with mark probability of 50 %. Then the data is modulated with an optical carrier frequency of 193.1THz, using optical QPSK modulator. The modulated optical signal passes through the free-space through transmitter telescope. At the receiver the optical signal is received with a receiver telescope and then optical to electrical (OE) conversion is done using a coherent optical QPSK demodulator. Afterward the signal is passed through a low pass Bessel's filter for eliminating the noise. Using a data recovery circuit the information is regenerated.

In between the two DL setups of the hybrid communication system, fiber based DWDM setup is incorporated for long haul communication as shown in Fig.2. The fiber based DWDM setup consists of a transmitter, optical fiber as the propagation medium and the receiver. The transmitter consists of eight number of MDRZ modulators, and then these outputs are fed to the multiplexer. The output of the multiplexer is given to the fiber in symmetrical dispersion compensation configuration as shown in Fig. 2. Here each fiber span consists of 50km of SSMF and 10km of DCF with erbium doped fiber amplifiers (EDFA) to amplify the optical signal. At the receiver optical to electrical (OE) conversion is done using a MDRZ demodulator. It consists of PIN diode, low pass Bessel's filter for suppressing the noise and data recovery circuit to regenerate the information. Also the setup uses various visualizers such as optical spectrum analyzer (OSA), for observing the optical signal spectrum, bit error rate (BER) analyzer for observing the eye diagram, Q-value and BER of the system. The BER value acceptable is 10^{-9} to 10^{-15} for an optical communication link [11]. For error free communications, the forward error correction (FEC) threshold, that is the BER should be less than or equal to 10^{-12}, which correspond to a Q-factor of greater than or equal to 6.8 [14]. Thus all optical links with Q-factor greater than or equal to 6.8 is suitable for data communication.

7. Simulation

The proposed hybrid optical communication system shown in Fig. 2 is designed and simulated using optisystem 9.0. The results are analyzed in MATLAB 7.9 environment. Optisystem is a numerical simulation software that enables the users to plan, test and simulate all types of optical link in the physical layer across the broad spectrum of optical networks. Within the software algorithms are included for bit error rate calculation, dispersion map design, system penalty estimations [15]. The details regarding the simulation parameters used are given in Table 2, 3 and 4. The simulation parameters used are as per the practical scenario of the optical hybrid communication system. The bit-rate considered is 160Gbps, 100Gbps and 40Gbps as per the ITU-T guidelines [10].

8. Results and discussion

At first, the proposed fiber based DWDM setup is designed and simulated for different modulation formats. The latest modulation formats for the setup is used here. They are carrier suppressed return to zero (CSRZ), duo-binary

Table 1. I and Q signal as per the incoming symbol

Symbol	I Signal	Q Signal
00	1	0
01	0	1
10	0	-1
11	-1	0

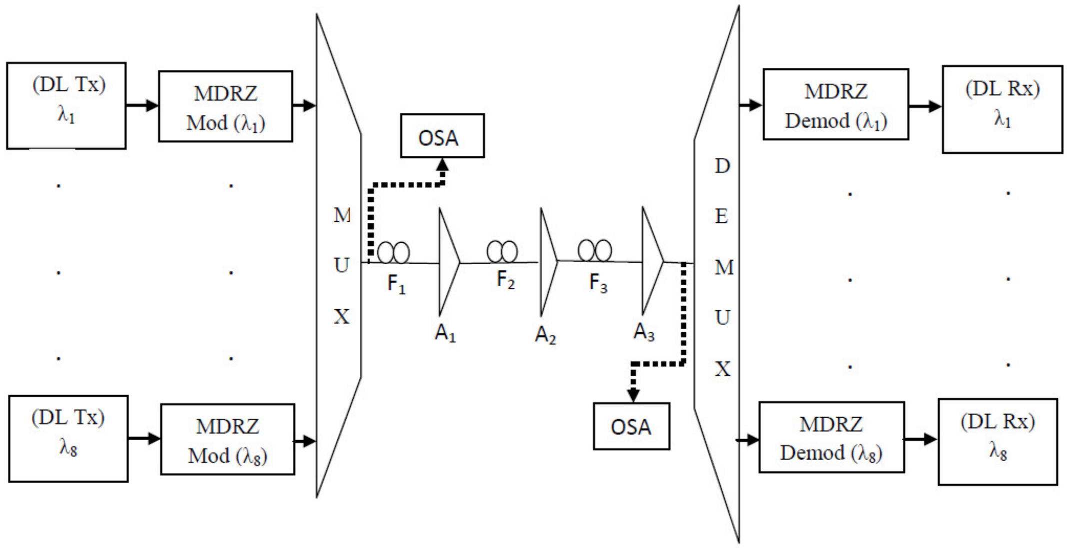

Fig. 2. Block diagram of the proposed hybrid optical communication system

return to zero (DRZ) and modified duo-binary return to zero (MDRZ) modulation formats. Fig. 3 shows the coverage distance of the setup for various modulation formats at different bit-rates. From Fig. 3, we can conclude that the optimized modulation format for the setup is the MDRZ modulation format, as its performance is the best comparing to other modulation formats. Fig.4 shows the Q-factor of the setup for all the channels for the coverage distance of 50km and 450km using the MDRZ modulation format at the bit-rate of 160Gbps/channel. It can be concluded here that as the coverage distance increases, Q-factor decreases. It is observed that for the coverage distance of 450km, the Q-factor of all the channels are greater than or equal to forward error correction (FEC) threshold value 6.8 (BER $\leq 10^{-12}$). Beyond this coverage distance, the Q-factor obtained is less than 6.8 (BER $\geq 10^{-12}$). Hence we can conclude that the optimized coverage distance of the proposed setup is 450km. Fig. 5 shows the multiplexed output (at the receiver) optical spectrum of the setup. From the output spectrum, we can conclude that the end channels of the output spectrum contains more spurious signals and it is due to the non linear effect of fiber that is the four wave mixing (FWM) effect of the fiber optic DWDM system.

Then the DL setups is designed and connected to either end of the fiber optic DWDM setup. The modulation formats used for the DL setup are return-to-zero (RZ), non-return-to-zero (NRZ) and coherent optical quadrature phase shift keying (QPSK) modulation formats. Fig. 6 shows the coverage distance of the setup for various modulation formats at different bit-rates. From this figure, we can conclude that the optimized modulation format for the setup is

Table 2. Simulation parameters of fiber based DWDM setup

Parameters	values
Bit rate per channel	160Gbps, 100Gbps, 40Gbps
Sequence length	512
Samples/bit	64
Number of channels	8
Frequency spacing between channels	320GHz
Input power	10dBm
Centre channel operating frequency	193.1THz
Distance	50km x N spans
EDFA noise figure	6dB

Table 3. Fiber parameters

Fiber type	Attenuation $(\frac{dB}{km})$	Dispersion $(\frac{ps}{km-nm})$	Dispersion slope $(\frac{ps}{km-nm^2})$	Effective core area (μm^2)
SMF	0.200	17	0.075	70
DCF	0.500	-85	-0.300	22

Table 4. Simulation parameters of optical wireless diffused link

Parameters	values
Bit rate per channel	160Gbps, 100Gbps,40Gbps
Sequence length	512
Samples/bit	64
Input power	5dBm
Local oscillator power at receiver	0dBm
Modulation	Coherent optical QPSK
Centre channel optical QPSK transmitter frequency	193.1THz
Frequency spacing between channels	320GHz
Attenuation of free space	200dB/km
Transmitter aperture diameter	5cm
Receiver aperture diameter	7.5cm

Table 5. Summery of the optimized coverage distance of the proposed hybrid communication system

Bit rate per channel	Optimized coverage distance for DWDM fiber optic link	Optimized coverage distance for wireless optical diffused link
160Gbps	450km	126m
100Gbps	650km	134m
40Gbps	750km	154m

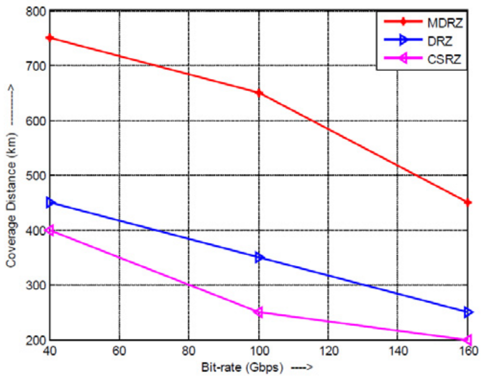

Fig. 3. Coverage distance with respect to bit-rate for various modulation formats of DWDM fiber setup

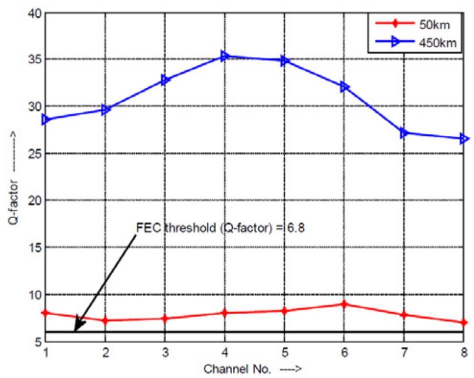

Fig. 4. Q-factor of all channels for the MDRZ modulation format

the coherent optical QPSK modulation as its performance is the best comparing to other modulation formats. Fig. 7 shows the eye diagram and Q-factor of the setup at a distance of 126m employing coherent optical QPSK modulation technique at the bit-rate of 160Gbps/channel. The eye observed is a very clear one as fresh 0s and 1s are regenerated from the distorted received signal. The Q-factor observed is 2258.4. Fig. 8 shows the signal constellation diagram at

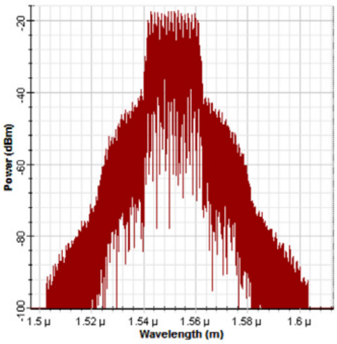

Fig. 5. Multiplexed output optical spectrum of the DWDM fiber setup (160Gbps)

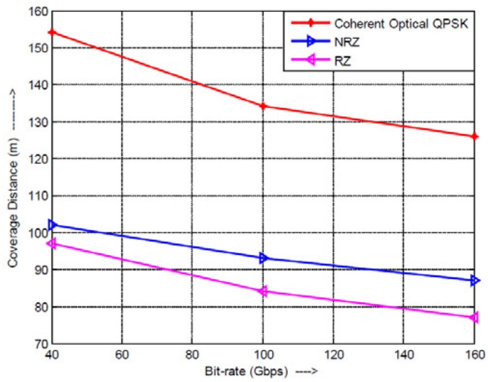

Fig. 6. Coverage distance with respect to bit-rate for various modulation formats of DL setup

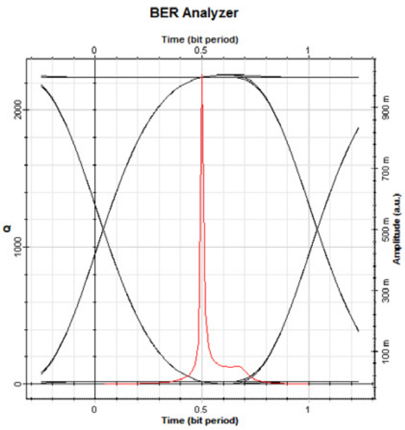

Fig. 7. Eye diagram and Q-factor of the DL setup (160Gbps) at a distance of 126m

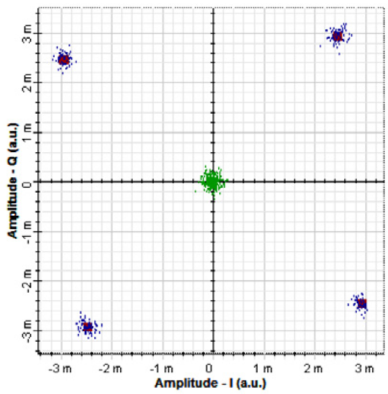

Fig. 8. Signal constellation diagram of the DL setup (160Gbps) at a distance of 126m

the receiver of the setup, and it is as expected for the QPSK modulation technique. Hence we can conclude that the signal is obtained faithfully at the receiver at a coverage distance of 126m.

Fig. 9 and 10 show the input and output time domain signal of the hybrid setup, which show that there is a strong correlation between the input and output signal. Thus we can conclude that the signal is recovered faithfully as it is expected. Similarly the system is simulated for 100Gbps/chennel and 40Gbps/channel bit-rate. Table 5 summaries the coverage distance of the hybrid setup employing optimized modulation formats for various bit rates.

9. Conclusion

We have presented an optimized hybrid optical communication system for bit-rates of 160Gbps/ channel, 100Gbps/ channel and 40Gbps/channel. It consists of optical fiber based 8-channel DWDM setup for long-haul, point to point communication and wireless optical diffused link for short-haul, multicasting applications. The use of wireless optical diffused link at either end solves the last mile and first mile problem of the today's optical communication network where as the fiber optic DWDM link solves the reachability problem in long-haul point to point communication system. The proposed fiber optic DWDM system uses symmetrical dispersion compensation technique, along with the optimized modified duo-binary return-to-zero modulation format. At the same time, the wireless optical

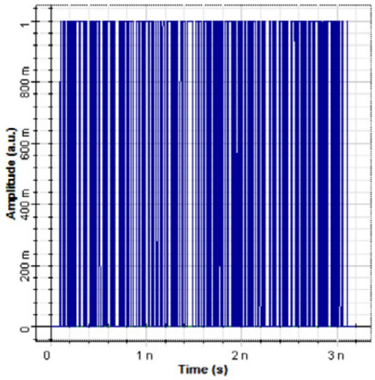

Fig. 9. Input electrical time domain signal of the hybrid setup of channel No. 8 (160Gbps)

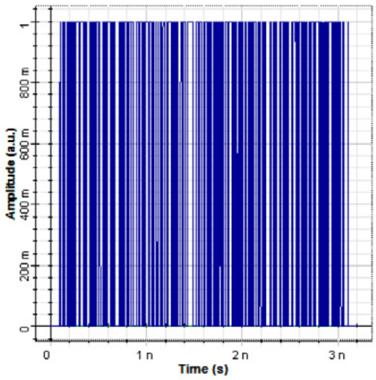

Fig. 10. Output electrical time domain signal of the hybrid setup of channel No. 8 (160Gbps)

diffused link uses the optimized coherent optical quadrature phase shift keying modulation technique. For a bit rate of 160Gbps/channel, the optimized coverage distance found is 126m for wireless optical diffused link and 450km for fiber optic link. The proposed system will be highly useful for present and next generation long distance optical communication systems and computer networks. The system may further be analyzed for more number of input channels and also for higher coverage distance.

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