Performance Evaluation of Two-Hop Wireless Link under Rayleigh and Nakagami-m Fading Channel for 8-PSK and 16-QAM

Abu Sayed Md. Mostafizur Rahaman, Md. Imdadul Islam, and M. R. Amin

Abstract—**One of the major challenges in wireless communications, especially in urban area, is to detect the digital data under different fading environment and additive white Gaussian noise (AWGN). In a two-hop wireless links, each link is affected by fading and noise which degrades the overall performance of the communication system. In this paper performance of two-hop link is analyzed under Rayleigh and Nakagami-m fading environments separately for 8-PSK and 16-QAM modulation schemes. The objective of the paper is to observe the relative impact of two fading environments on the two above mentioned modulation schemes if no combining scheme or error correction measure is taken on the repeater station.**

Index Terms—**Probability of symbol error, AWGN, coherent demodulator, channel state information (CSI), average power scaling (APS), Gaussian Q function.**

I. Introduction

The electromagnetic (EM) wave in wireless channel may be reflected, refracted and scattered by surrounding objects which results in multipath propagation of the signal. Therefore, multiple copy of the same signal arrives at the receiving end and creates delay spread. When separation between the transmitter and the receiver is very large then mean signal strength is considered at the receiver (known as large scale propagation model) but when separation between the transmitter and the receiver is small (less than 5 km), usually in an urban or suburban area, then rapid variation of the signal strength within short distance or short duration is considered (known as small scale propagation model). Under a multipath propagation environment, the amplitude and phase of a composite modulated symbol vary widely and rapidly, a phenomenon known as fading. Two most important parameters of a fading channel are coherence time and coherence bandwidth [1]. A lot of other parameters like: symbol period, multipath delay spread, Doppler spread, coherence time/ bandwidth, time variant or invariant channel property, channel gain etc. play vital role on the performance of a wireless link as summarized in [1],[2].

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A channel may be time-selective or frequency-selective depends on the time-varying nature of the impulse response of the channel. Finally, from the auto-correlation of channel impulse response, the channel may be classified as wide-sense stationary (WSS), uncorrelated scattering (WS) or wide-sense stationary uncorrelated scattering (WSSNS) channel. The complex envelope of a modulated wave is a random variable (RV) may follow Rayleigh, Ricean, or Nakagami-m distribution depending on the condition of the channel. For example, if there is a strong line-of-sight (LOS) between the transmitter and the receiver along with multipath fading, the distribution follows Ricean probability density function (PDF) instead of Rayleigh PDF. Present literature shows the performance of multi-hop wireless link applicable in ad-hoc network under fading environment [3]. For example, Ref. [4] determines the average bit error probability (ABEP) for BPSK, QPSK and M-QAM under Nakagami-m channels. In [5], the performance of dual-hop relay link is considered for coherent and non-coherent binary modulation when the relay stream only for amplify-and-forward (AF). The propagation took Nakagami-m fading considering both single antenna and selection combining scheme. The paper also claims to derive the generalized expression for bit error probability (BEP) of all binary modulation schemes.

The paper [6] shows the performance of cooperative diversity wireless link (in addition to direct link between the transmitter and the receiver, some neighboring nodes also relay the signal) under Nakagami-m fading environment based on the concept of [3]. In [7], M-QAM scheme combined with multiuser diversity and Nakagami-m fading channels has been studied. The paper considers a channel estimator at each mobile station (MS) and an error-free feedback path is considered from the MS and the base station (BS) with a delay time τ. The impact of the feedback delay on the average bit error rate (BER) for different values of m are shown explicitly. We know that BER depends on the signal-to-noise ratio (SNR) and the size of the constellation. In feedback model of the paper, the transmitter determines the size of the constellation upon getting the feedback SNR. If feedback delay τ is much greater than the symbol period the previous constellation is combined until getting the feedback SNR which incurs some additional error. The paper includes multiuser diversity as considered in [8]. In [9] , the outage probability and average BEP is evaluated for a two-hop communication system under mixed Rayleigh and Ricean fading channels.

In the present paper, performance of two-hop link is analyzed under Rayleigh and Nakagami-m fading environments separately for 8-PSK and 16-QAM modulation schemes. The objective of the paper is to observe the relative impact of two fading environments on the two above mentioned modulation schemes if no combining scheme or error correction measure is taken on the repeater station. Both the fading types severely affect the two-hop link and hence some additional techniques like: adaptive equalization, combining scheme of multiple input multiple output (MIMO), incorporation of space-time block code (STBC) etc. are recommended to enhance the performance of such links.

The rest of the paper is organized as follows. Section II provides the system model of a two-hop wireless link under Rayleigh/Nakagami-m channel. Section III gives the result of the paper and finally, Sec. IV concludes the entire analysis.

II. System Model

In a dual-hop wireless communication system the sender node S communicates with the detector node D through the relay station R as shown in Fig. 1. Let us first concentrate on the analytical solution of the probability of symbol error P_s under an AWGN environment.

In M-PSK modulation scheme, the received signal vector of coherent demodulator on $\Phi_1(t)$ - $\Phi_2(t)$ plane is

$$\mathbf{r} = \begin{bmatrix} r_1 \\ r_2 \end{bmatrix},$$

where

$$r_1 = \int_0^T \{S_i(t) + n(t)\}\Phi_1(t)dt = \sqrt{E}\cos\theta_i + n_1 ,$$

$$r_2 = \int_0^T \{S_i(t) + n(t)\}\Phi_2(t)dt = \sqrt{E}\sin\theta_i + n_2 ,$$

and $S_i(t)$ is the i-th modulated wave in the region $kT \le t \le (k+1)T$, E is the energy of a symbol, n_1 and n_2 are the noise of the in-phase and quadrature component of the received signal.

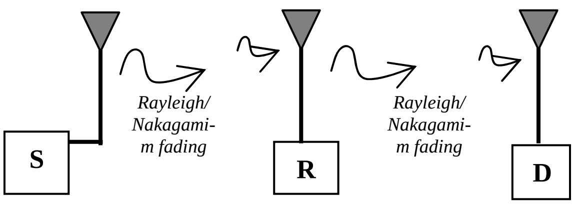

Fig. 1 Two-hop wireless link.

Taking $r_1 = \rho\cos\hat{\theta}_i$ and $r_2 = \rho\sin\hat{\theta}_i$, the joint probability density function (pdf) of ρ and $\hat{\theta}_i$ given $S_i(t)$ is transmitted can be written as [10]:

$$p\{\rho, \hat{\theta}_i | S_i(t) \text{ transmitted}\} = \frac{1}{\pi N_0}\exp\left[-\frac{1}{N_0}\left\{\rho^2 + E - 2\rho\sqrt{E}\cos(\theta_i - \hat{\theta}_i)\right\}\right]. \tag{1}$$

Integrating both side of Eq. (1) with respect to ρ and taking $\varphi = \hat{\theta}_i - \theta_i \in [-\pi, \ \pi]$, the pdf of φ becomes

$$p\{\varphi | S_i(t) \text{ transmitted}\} = \frac{e^{-E/N_0}}{2\pi} \times\left[1+\sqrt{\frac{\pi E}{N_0}}(\cos\varphi)e^{-(E/N_0)\cos^2\varphi}\left\{1+erf\left(\sqrt{\frac{E}{N_0}}\cos\varphi\right)\right\}\right]. \tag{2}$$

The probability of symbol error [10] for $M > 4$ is

$$P_s = 1 - \int_{-\pi/M}^{\pi/M} p\{\varphi | S_i(t) \text{ transmitted}\}d\varphi = \frac{M-1}{M} - 0.5erf\left\{\sqrt{\frac{E}{N_0}}\sin\left(\frac{\pi}{M}\right)\right\} - \frac{1}{\sqrt{\pi}} \times \int_0^{\sqrt{E/N_0}\sin(\pi/M)} e^{-y^2} erf\left(y\cot\left(\frac{\pi}{M}\right)\right)dy. \tag{3}$$

If $E/N_0 >> 1$, then

$$P_s \approx 2Q\left(\sqrt{\frac{2E}{N_0}}\sin\left(\frac{\pi}{M}\right)\right). \tag{4}$$

In square M-QAM, the symbol error probability is

$$P_s = 2P_{\sqrt{M}} - P_{\sqrt{M}}^2 , \tag{5}$$

where

$$P_{\sqrt{M}} = \frac{2\left(\sqrt{M}-1\right)}{\sqrt{M}}Q\left(\sqrt{\frac{3E_{av}}{(M-1)N_0}}\right),$$

$E_{av} = 0.5T\,E[A_i^2]$, T is the period of a symbol and A_i is the amplitude of the i-th symbol.

In a slow-fading channel, the instantaneous SNR per bit, $\gamma = E/N_0$ is a time invariant RV with PDF $f_\Gamma(\gamma)$ which depends on the fading environment. The average probability of error can be found for a fading channel as [11]

$$P_e = \int_0^\infty P_s(\gamma)f_\Gamma(\gamma)d\gamma . \tag{6}$$

In this paper we only consider Rayleigh and Nakagami-m fading channels, their PDFs are given respectively by:

$$f_\Gamma(\gamma)\Big|_{Rayleigh} = \frac{1}{\gamma_{avg}}e^{-\gamma/\gamma_{avg}} , \tag{7}$$

and

$$f_\Gamma(\gamma)\Big|_{Nakagami-m} = \frac{m^m\gamma^{m-1}}{\gamma_{avg}^m\Gamma(m)}e^{-m\gamma/\gamma_{avg}} , \tag{8}$$

where m is the Nakagami-m fading parameter which ranges from 1/2 to ∞. Now combining Eqs. (3), (6) and (7), the symbol error probability of 8-PSK under Rayleigh fading is written as

$$P_e = \int_0^{\infty} \left[\frac{0.875 - 0.5erf\left(0.3827\sqrt{\gamma}\right) - 0.5642I}{\gamma_{av}} \right] e^{-\gamma/\gamma_{av}} d\gamma, \tag{9}$$

where

$$I = \int_0^{0.5\sqrt{\gamma(2-\sqrt{2})}} e^{-y^2} erf\left\{ \frac{y\sqrt{\left(2+\sqrt{2}\right)}}{\sqrt{\left(2-\sqrt{2}\right)}} \right\} dy .$$

Combining Eqs. (3), (6) and (8), the symbol error probability of 8-PSK under Nakagami-m fading is written as

$$P_e = \int_0^{\infty} 4 \left[\frac{0.875 - 0.5erf\left(0.3827\sqrt{\gamma}\right) - 0.5642I}{\gamma_{av}} \right] \times \left(\frac{\gamma}{\gamma_{av}^2} \right) e^{-2\gamma/\gamma_{av}} d\gamma; \quad m = 2. \tag{10}$$

Similarly, for 16-QAM the symbol error rate under Rayleigh fading is derived as,

$$P_e = \int_0^{\infty} 3\sqrt{\frac{2}{\pi}} \left[\frac{\sqrt{2\pi}}{2} erf\left(200 - \sqrt{2}\right)\right) - \frac{\sqrt{2\pi}}{2} erf\left(\sqrt{10\gamma} - \sqrt{2}\right)\right) \right] \times e^{-\gamma/\gamma_{av}} d\gamma. \tag{11}$$

For Nakagami case of $m = 2$,

$$P_e = \int_0^{\infty} 3\sqrt{\frac{2}{\pi}} \left[\frac{\sqrt{2\pi}}{2} erf\left(200\sqrt{2}\right)\right) - \frac{\sqrt{2\pi}}{2} erf\left(\sqrt{\frac{\gamma}{10}} \right) \right] \times \frac{\gamma}{\gamma_{avg}^2} e^{-2\gamma/\gamma_{av}} d\gamma. \tag{12}$$

Let us consider the generalized form of the symbol error probability of different modulation schemes using Gaussian Q function like, $Q(g\sqrt{\gamma})$; where g is a constant which depends on the particular modulation scheme and detection technique (for example, $g = \sqrt{2}$ for BPSK and $g = 1$ for QPSK).

The Q-function can be written as (please see Appendix A):

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_0^{\infty} e^{-y^2/2} dy = \frac{1}{\pi} \int_0^{\pi/2} \exp\left[-\frac{x^2}{2\sin^2\theta} \right] d\theta .$$

Using this expression for the Q-function, the probability of bit error P_e can be written as

$$P_e = \int_0^{\infty} Q(g\sqrt{\gamma}) f_\Gamma(\gamma)\, d\gamma . \tag{13}$$

From moment generating function,

$$M_R(t) = E\left[e^{tR}\right] = \int_0^{\infty} e^{tr} P_R(r) dr$$

$$= \frac{1}{\pi} \int_0^{\infty} \int_0^{\pi/2} e^{-g^2\gamma/2\sin^2\theta} f_\Gamma(\gamma)\, d\theta\, d\gamma$$

By substituting $-s$ for t, we get

$$M_R(-s) = \int_0^{\infty} e^{-sr} P_R(r) dr . \tag{14}$$

From Eqs. (12) and (13), we have

$$P_e = \frac{1}{\pi} \int_0^{\pi/2} M_\Gamma\left(-\frac{g^2}{2\sin^2\theta} \right) d\theta . \tag{15}$$

The Laplace transform of Rayleigh PDF is

$$M_\Gamma(-s) = \frac{1}{1 + s\gamma_{avg}}; \; s > 0 .$$

Therefore,

$$P_{e\_Rayleigh}\left(\gamma_{avg}\right) = \frac{1}{\pi} \int_0^{\pi/2} \left(1 + \frac{g^2\gamma_{avg}}{2\sin^2\theta} \right)^{-1} d\theta = \frac{1}{2}\left\{ 1 - \sqrt{\frac{g^2\gamma_{avg}/2}{1 + g^2\gamma_{avg}/2}} \right\}. \tag{16}$$

Similarly, for Nakagami-m case, we have

$$M_\Gamma(-s) = \left(1 + \frac{s\gamma_{avg}}{n} \right)^{-m} ; \; s > 0$$

and thus

$$P_{e\_Nakagami-m}\left(\gamma_{avg}\right) = \frac{1}{\pi} \int_0^{\pi/2} \left(1 + \frac{a^2\gamma_{avg}}{2m\sin^2\theta} \right)^{-m} d\theta. \tag{17}$$

Analytical solution of the above equation, Eq. (17), is very complicated and hence numerical solution is preferable to plot the performance of the Nakagami-m fading channel.

The end to end instantaneous SNR of the dual-hop AF (amplify-and-forward) and instantaneous power scaling (IPS) relay system is given as [12],[13]:

$$\gamma_{combined} = \frac{\gamma_{SR}\gamma_{RD}}{\gamma_{SR} + \gamma_{RD}}, \tag{18}$$

where $\gamma_{SR} = \alpha_1^2 E_{SR} / N_0$, $\gamma_{RD} = \alpha_2^2 E_{RD} / N_0$. The parameters α_1 and α_2 are the fading amplitudes of the S-R and R-D links respectively.

For fixed-gain also called 'average power scaling' (APS) of relay station, the end to end instantaneous SNR of the dual-hop link [13], [14] is:

$$\gamma_{combined} = \frac{\gamma_{SR}\gamma_{RD}}{C + \gamma_{RD}}, \tag{19}$$

where $C = 1 + E_{SR} / N_0$. If gain G of the repeater is selected according to the channel state information (CSI) [9], we have

$$\gamma_{combined} = \frac{\gamma_{SR}\gamma_{RD}}{C + \gamma_{RD} + \gamma_{SR}}, \tag{20}$$

where $C = 1$ for exact $\gamma_{combined}$ and $C = 0$ for well approximate at higher SNR.

Now combination of Eqs. (9), (10), (15) and (17)-(20) will provide performance of a dual hop Raylegh and Nakagami-m fading channel.

III. Results and Discussions

In Fig. 2, the symbol error probability P_S is plotted against average SNR in dB from 2dB to 14dB for single hop link for 8-PSK and 16-QAM (square constellation). Two fading PDFs: Rayleigh and Nakagami-m (for m = 2) are used and both modulation schemes are severely affected by the fading as is visualized from Fig. 2. The phenomenon can be explained as follows: the symbol error probability under fading environment is much higher than the theoretical value of P_e of both modulation techniques under AWGN channel.

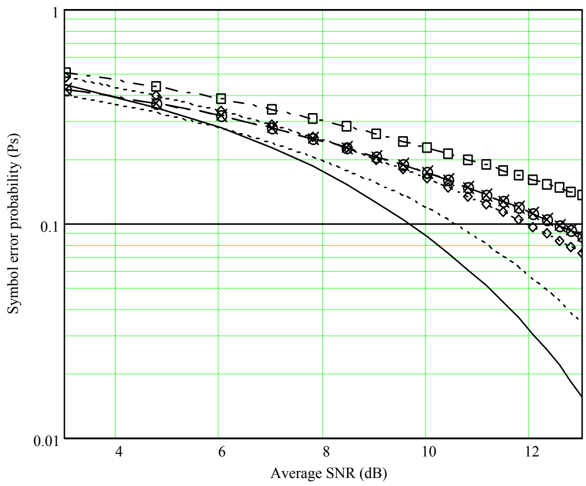

Fig. 2 Comparison of theoretical SER and SER of fading channel for single hop wireless link.

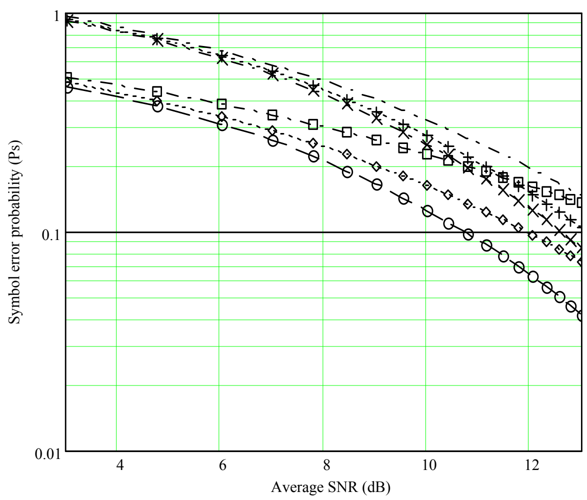

Fig. 3 Comparison of performance of single and dual hop fading channel for 8-PSK scheme.

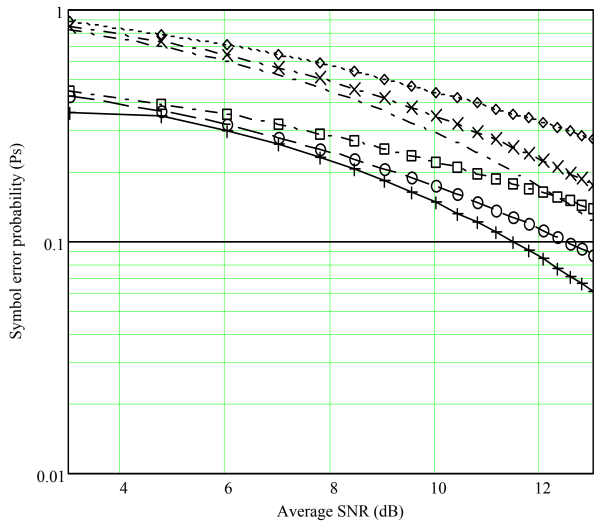

Fig. 4 Comparison of performance of single and dual hop fading channel for 16-QAM scheme.

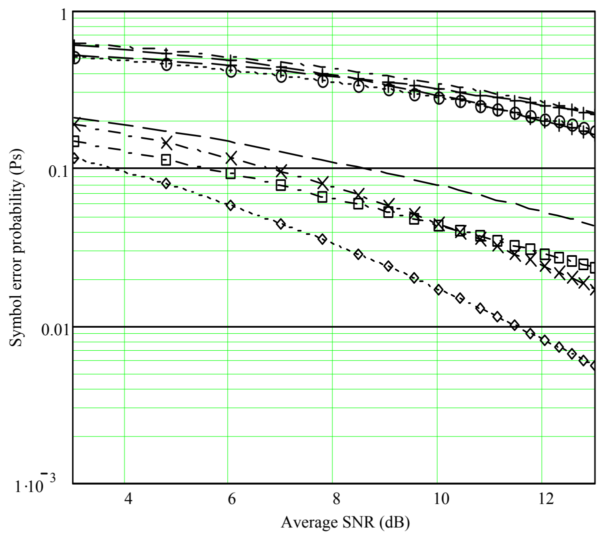

Fig. 5 Comparison of modulation scheme on two hop link.

Figure 3 shows the variation of P_S against average SNR (measured in dB) of fading channel for both single- and dual-hop link for 8-PSK cases. The performance of dual-hop link is much inferior to that of a single- link for both fading cases at the same time the separation between the curves of single- and dual-hop increases with increase in SNR. The phenomenon can be explained as follows: the performance of second-hop depends on that of first-hop since we have not considered any type of combining scheme or forward error correction technique on the repeater. On the other hand, the performance of the Rayliegh fading channel is worse than that of the Nakagami-*m* (for $m = 2$) case as is also visualized from Fig. 3. For Nakagami-*m* fading channel performance is improved with the increment of *m* as is shown in Fig. 3 for the case of m =2, 3 and 4.

Similar analysis is shown in Fig. 4 for 16-QAM and the relative performance are found to be similar to that of Fig. 3. Comparing Fig. 3 and Fig. 4 it is found that P_S for all the cases of 16-QAM is higher than that of 8-PSK which can be explained from the signal space concept of [10]. To observe the phenomenon, Fig. 5 compares the probability of symbol error for the following four different modulation schemes: BPSK, QPSK, 8-PSK and 16-QAM for both types of fading (two-link case) where the performance are found according to the signal space of the constellation of the modulation schemes. The two links may be affected by two different types of fading like: 1st hop is affected by Rayleigh fading and 2nd hop is affected by Nakagami-m fading or vice versa. Most of the previous works do the similar job using combination of STBC and maximal ratio combining (MRC) using multiple antenna system at one or two terminals. In this paper we have used single antenna system at each of three terminals without any combining scheme so the performance of our model will be worse than previous works but our model is applicable to ad-hoc network rather than the previous models mentioned in Sec. I.

IV. Conclusion

The paper finds the performance of two-hop wireless link under Rayleigh and Nakagami-m fading channels for two widely used modulation schemes of 8-PSK and 16-QAM of wireless communications system. Both the fading types severely affect the two-hop link and hence some additional techniques like: adaptive equalization, combining scheme of MIMO/SIMO/MISO, incorporation of STBC etc. are recommended to enhance the performance of such links. Although in recent time a good number of papers deal with similar analysis for the case of multiple antennas at sender and receiver sides with single antenna on the repeater, the analysis becomes very complicated, however the performance is improved. In context of real life applications, like ad-hoc networks, single antenna model of our present paper is more appropriate.

Appendix

From [11] and [15] (5, Eq. (3.363.2), we have

$$\int_u^{\infty} \frac{e^{-\alpha x}}{x\sqrt{x-u}}dx = \frac{\pi}{\sqrt{u}} erfc(\sqrt{u\alpha})\,. \tag{a.1}$$

Multiplying both side by $e^{\alpha u}$ and putting $u = y^2$, Eq. (a.1) becomes

$$\int_{y^2}^{\infty} \frac{e^{-\alpha x}e^{\alpha y^2}}{x\sqrt{x-y^2}}dx = \frac{\pi}{y} e^{\alpha y^2} erfc(y\sqrt{\alpha})$$

$$\Rightarrow \int_0^{\infty} \frac{e^{-\alpha z}}{\left(z+y^2\right)\sqrt{z}}dz = \frac{\pi}{y} e^{\alpha y^2} erfc(y\sqrt{\alpha})\,;$$

[by substituting $z = x - y^2$]

$$\Rightarrow \int_0^{\infty} \frac{e^{-\alpha s^2}}{\left(s^2+y^2\right)}ds = \frac{\pi}{2y} e^{\alpha y^2} erfc(y\sqrt{\alpha})\,;$$

[by substituting $z = s^2$]

$$\Rightarrow \frac{2}{\pi}\int_0^{\infty} \frac{e^{-r^2\left(s^2+1\right)}}{s^2+1}ds = erfc(r)\,;$$

[by substituting $y = 1$ and $\alpha = r^2$]

$$\Rightarrow \frac{2}{\pi}\int_0^{\pi} \exp\left[-\frac{r^2}{\sin^2\theta}\right]d\theta = erfc(r)\,;$$

$$\left[\text{by substituting } \sin^2\theta = \frac{1}{s^2+1}\right].$$

Therefore, after substituting $r = x/\sqrt{2}$, finally we obtain

$$Q(x) \equiv erfc\left(x/\sqrt{2}\right) = \frac{2}{\pi}\int_0^{\pi} \exp\left[-\frac{x^2}{2\sin^2\theta}\right]d\theta\,. \tag{a.2}$$

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