gain of the \( l \)th diversity branch is denoted by \( \hat{h}_l(t) \) and \( n_l(t) \) designates the corresponding additive white Gaussian noise (AWGN) component with variance \( N_0 \). The relationship between the transmitted signal \( s(t) \) and the received signals \( x_l(t) \) at the combiner input can be expressed as

\[
x(t) = \hat{h}(t)s(t) + n(t)
\]

where \( x(t), \hat{h}(t), \) and \( n(t) \) are \( L \times 1 \) vectors with entries corresponding to the \( l \)th (\( l = 1, 2, \ldots, L \)) diversity branch denoted by \( x_l(t), \hat{h}_l(t), \) and \( n_l(t) \), respectively. The spatial correlation between the diversity branches arises due to the spatial correlation between closely located receiver antennas in the antenna array. The correlation matrix \( R \), describing the correlation between diversity branches, is given by \( R = E[\hat{h}(t)\hat{h}^H(t)] \) [36]. Here, the entries of the \( L \times 1 \) vector \( \hat{h}(t) \) are mutually uncorrelated with amplitudes and phases given by \( |h_l(t)| \) and \( \phi_l \), respectively. We have assumed that the phases \( \phi_l (l = 1, 2, \ldots, L) \) are uniformly distributed over \((0, 2\pi)\), while the envelopes \( \xi_l(t) = |h_l(t)| \) (\( l = 1, 2, \ldots, L \)) follow the Nakagami-\( m \) distribution \( p_\xi(z) \) given by [21]

\[
p_\xi(z) = 2m_\xi^mz^{2m_\xi-1}\frac{e^{-m_\xi z}}{\Gamma(m_\xi)\Omega_\xi^m}, \quad z \geq 0
\]

where \( \Omega_\xi = E\{\xi_l^2(t)\} \), \( m_\xi = \Omega_\xi^2/\text{Var}\{\xi_l^2(t)\} \), and \( \Gamma(\cdot) \) represents the gamma function [44]. Here, \( E\{\cdot\} \) and \( \text{Var}\{\cdot\} \) denote the mean (or the statistical expectation) and variance operators, respectively. The parameter \( m_\xi \) controls the severity of the fading. Increasing the value of \( m_\xi \) decreases the severity of fading associated with the \( l \)th branch and vice versa.

The eigenvalue decomposition of the correlation matrix \( \mathbf{R} \) can be expressed as \( \mathbf{R} = \mathbf{U} \mathbf{\Lambda} \mathbf{U}^H \). Here, \( \mathbf{U} \) consists of the eigenbasis vectors at the receiver and the diagonal matrix \( \mathbf{\Lambda} \) comprises the eigenvalues \( \lambda_l \) (\( l = 1, 2, \ldots, L \)) of the correlation matrix \( \mathbf{R} \). The receiver antenna correlations \( \rho_{p,q} \) (\( p, q = 1, 2, \ldots, L \)) under isotropic scattering conditions can be expressed as \( \rho_{p,q} = J_0(b_{pq}) \) [45], where \( J_0(\cdot) \) is the Bessel function of the first kind of order zero [44] and \( b_{pq} = 2\pi\delta_{pq}/\lambda \). Here, \( \lambda \) is the wavelength of the transmitted signal, whereas \( \delta_{pq} \) represents the spacing between the \( p \)th and \( q \)th receiver antennas. In this article, we have considered a uniform linear array with adjacent receiver antennas separation represented by \( \delta_R \). Increasing the value of \( \delta_R \) decreases the spatial correlation between the diversity branches and vice versa. It is worth mentioning here that the analysis presented in this article is not restricted to any specific receiver antenna correlation model, such as given by \( J_0(\cdot) \), for the description of the correlation matrix \( \mathbf{R} \). Therefore, any receiver antenna correlation model can be used as long as the resulting correlation matrix \( \mathbf{R} \) has the eigenvalues \( \lambda_l \) (\( l = 1, 2, \ldots, L \)).

### A. Spatially Correlated Nakagami-\( m \) Channels with MRC

In MRC, the combiner computes \( y(t) = \hat{h}^H(t)x(t) \), hence the instantaneous SNR \( \gamma(t) \) at the combiner output in an MRC diversity system with correlated diversity branches can be expressed as [9, 30]

\[
\gamma(t) = \frac{P_s}{N_0} \hat{h}^H(t)\hat{h}(t) = \frac{P_s}{N_0} \sum_{l=1}^{L} \lambda_l \xi_l^2(t) = \gamma_s\Xi(t)
\]

where \( \gamma_s = P_s/N_0 \) can be termed as the average SNR of each branch, \( \Xi(t) = \sum_{l=1}^{L} \xi_l^2(t) \), and \( \xi_l^2(t) = \sqrt{N_0} \xi_l(t) \). It is worth mentioning that although we have employed the Kronecker model, the study in [30] reports that (3) holds for any arbitrary correlation model, as long as the correlation matrix \( \mathbf{R} \) is non-negative definite. It is also shown in [30] that despite the diversity branches are spatially correlated, the instantaneous SNR \( \gamma(t) \) at the combiner output of an MRC system can be expressed as a sum of weighted statistically independent gamma variates \( \xi_l^2(t) \), as given in (3). The PDF \( p_{\xi_l^2}(z) \) of processes \( \xi_l^2(t) \) follows the gamma distribution with parameters \( \alpha_l = m_l \) and \( \beta_l = \lambda_l \Omega_l/m_l \) [46, Eq. (1)]. Therefore, the process \( \Xi(t) \) can be considered as a sum of weighted independent gamma variates. As a result, the PDF \( p_{\Xi}(z) \) of the process \( \Xi(t) \) can be expressed using [46, Eq. (2)] as

\[
p_{\Xi}(z) = \prod_{l=1}^{L} \left( \frac{\beta_l}{\beta_l \hat{\beta}_l} \right)^{\alpha_l} \sum_{k=0}^{\infty} \frac{\epsilon_k z^{\alpha_l+k}}{\beta_l \hat{\beta}_l \Gamma(\alpha_l+k)} \sum_{l=1}^{L} \alpha_l + k \sqrt{L} \left( \sum_{l=1}^{L} \frac{\alpha_l + k}{\lambda_l + k} \right),
\]

where

\[
\epsilon_{k+1} = \frac{1}{k+1} \sum_{i=1}^{k+1} \left[ \sum_{l=1}^{L} \alpha_l \left( 1 - \frac{\hat{\beta}_l}{\beta_l} \right) \right] e^{-\xi_l^2(t)/\lambda_l}, \quad k = 0, 1, 2, \ldots
\]

with \( \epsilon_0 = 1 \) and \( \hat{\beta}_l = \min\{\beta_l\} \) (\( l = 1, 2, \ldots, L \)).

When using MRC, if the diversity branches are uncorrelated having identical Nakagami-\( m \) parameters (i.e., when in (3) \( \lambda_l = 1 \), \( l = 1, 2, \ldots, L \), \( \alpha_l = \alpha_2 = \cdots = \alpha_L = \alpha \), and \( \beta_1 = \beta_2 = \cdots = \beta_L = \beta \)), it is shown in [24] that the joint PDF \( p_{\Xi}(z, \hat{z}) \) of \( \Xi(t) \) and its time derivative \( \dot{\Xi}(t) \) at the same time \( t \), under the assumption of isotropic scattering can be written as

\[
p_{\Xi}(z, \hat{z}) = p_{\Xi}(z) \frac{1}{\sqrt{2\pi\sigma^2}}, \quad z \geq 0, |\hat{z}| < \infty
\]