A Linear MMSE Receiver for Multi-Antenna SWIPT-enabled Wireless Networks

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Abstract—In this paper, we evaluate the performance of a linear minimum mean square error (MMSE) receiver in the context of simultaneous wireless information and power transfer (SWIPT)-enabled cellular networks. In contrast to the existing works, where a single-antenna SWIPT architecture is mainly considered, we focus on the SWIPT performance of the multi-antenna receiver architecture, based on the antenna switching (AS) and power splitting (PS) techniques. Aiming to further boost the network performance, we investigate a scenario where the receivers have the capability to employ a successive interference cancellation (SIC) scheme. By leveraging tools from stochastic geometry, we establish an analytical and tractable framework to evaluate the information decoding (ID) and the energy harvesting (EH) success probabilities of the considered network topologies. Our results reveal that the ID performance achieved by the MMSE receiver outperforms that of the conventional maximum ratio combining, leading to an enhanced EH performance, for a given ID reliability constraint. Moreover, by allocating an equal fraction of resources for ID and EH purpose, the PS scheme outperforms the AS in terms of both ID and EH success probabilities.

Index Terms—SWIPT, successive interference cancellation, MMSE receiver, stochastic geometry.

I. INTRODUCTION

Beyond fifth generation (B5G)/sixth generation (6G) networks are anticipated to host the emerging concept of massive Internet of Things (mIoT), requiring ultra-reliable, energy-efficient and low latency communications [1]. Since the majority of user equipments (UEs) participating in the mIoT concept are widely battery-powered, the operation time of such devices has a significant impact on the overall network performance. To this end, simultaneous wireless information and power transfer (SWIPT) becomes a promising communication paradigm, which enables mIoT devices to extract both information and energy from the received radio-frequency (RF) signals, via the employment of an appropriate scheme, such as time switching (TS), power splitting (PS) or antenna switching (AS) [2], [3].

The concept of SWIPT technology is well investigated in the context of large-scale networks. In [4], the authors explored a SWIPT technique in intelligent reflecting surface (IRS)-aided cellular networks, revealing that the IRSs can promote the compensation of the high RF signal attenuation and thus enhance the energy harvesting (EH) performance. The work in [5] investigated SWIPT-enabled networks under the TS and the PS schemes from a macroscopic point-of-view, where the optimal partitioning parameters to achieve maximum joint information decoding (ID) and EH success probability have been demonstrated. Although the TS scheme was extensively investigated in the literature, the strict synchronization requirements pose a crucial drawback, motivating the utilization of the PS scheme [2]. Moreover, the AS scheme is an alternative low-complexity scheme for multi-antenna UEs, which has been overlooked.

In the context of large-scale networks, the multi-user interference is the dominant limiting factor of the network performance, which motivates a plethora of advanced receivers, diversity combining and interference mitigating techniques, such as the minimum mean square error (MMSE) receiver, the maximum ratio combining (MRC), the successive interference cancellation (SIC), etc. Under the special scenario where the interference can be treated as white noise, the MRC technique achieves the highest output signal-to-noise ratio [6]. However, the consideration of multi-user interference as white noise is an suboptimal assumption, especially in large-scale networks where the interference observed at different UEs’ antennas is spatially correlated [7]. By taking into account the interference impact, the MMSE receiver was indicated to achieve a maximum output signal-to-interference-plus-noise ratio (SINR) [8], [9]. The work in [8] derived the exact cumulative distribution function for the output SINR of an ideal MMSE receiver, where multiple interferers and Rayleigh fading channel were considered. In addition, the above-mentioned work was further extended in [9], by considering a random number of interferers, illustrating the optimal network density that offers the highest network spatial throughput. Moreover, motivated by the severe effect of the multi-user interference and the ever-increasing demand for higher communication reliability, many sophisticated techniques for the interference mitigation, have been developed, e.g. the SIC technique. The authors in [10] investigated the SIC technique in heterogeneous networks, indicating that the SIC technique can significantly improve the network performance.

In this paper, we study the SWIPT performance for multi-antenna UEs in the context of a linear MMSE receiver. In particular, the UEs employ either a PS or an AS scheme to simultaneously extract information and harvest energy from the re-
received RF signals, where a MMSE receiver is employed for ID purpose. In order to further enhance the network performance, a SIC technique is investigated to improve the ID performance of the UEs, via mitigating the strongest multi-user interfering signals. By using stochastic geometry tools, we analytically derive the ID and the EH success probabilities, where closed-form expressions are obtained for the interference-limited scenarios. Our results show that the MMSE receiver achieves higher ID and EH success probabilities, compared with the conventional MRC. Moreover, it is demonstrated that, due to the MMSE receiver, the PS scheme outperforms the AS scheme in terms of both the ID and the EH performance. Finally, a significant gain of SWIPT performance can be achieved, by employing the SIC technique at the UEs.

Notation: $\Gamma(\cdot)$ and $\Gamma(\cdot, \cdot)$ denote the upper and the lower incomplete Gamma functions, respectively; $2F_1(\cdot, \cdot; \cdot; \cdot)$ is the Gauss hypergeometric function; $(\cdot)^H$ denotes the transpose conjugate; $(n)!$ denotes the factorial of $n$; $CN(0, \sigma^2 I_L)$ denotes the circularly symmetric complex Gaussian distribution with zero mean and covariance $\sigma^2 I_L$, $I_L$ is a $L \times L$ identity matrix; $\mathbb{C}^{1 \times L}$ denotes the vector of complex numbers of size $L$; and $\mathcal{G}(a, b)$ denotes the Gamma distribution with a shape and a scale parameter $a$ and $b$, respectively.

II. SYSTEM MODEL

A. Network model

We consider a single tier downlink cellular network consisting of a random number of base stations (BSs) and UEs. The locations of the BSs are modelled by a homogeneous Poisson process (PPP) $\Phi = \{x_i \in \mathbb{R}^2\}, i \geq 0$, with density $\lambda$, where $x_i$ represents the location of the $i$-th BS. Moreover, we assume that the UEs are uniformly distributed with a density $\lambda_u \gg \lambda$. Based on the Slivnyak’s theorem, we perform our analysis for the typical UE located at the origin, while our results hold for any UE in the network [11]. We assume that the BSs are sorted in ascending order with respect to their Euclidean distance from the origin, i.e. $r_1 \leq r_{i+1}$, $\forall x_i \in \Phi$, where $r_i = ||x_i||$. In addition, we assume that the typical UE communicates with the closest BS, i.e. the serving BS at $x_0$. Then, the probability density function (pdf) of the distance between the typical UE and the $i$-th BS, i.e. $r_i$, is given by [11]

$$f(r_i) = \frac{2(\pi \lambda)^{i+1}}{\Gamma(i+1)} r_i^{2i+1} \exp\left(-\pi \lambda r_i^2\right). \quad (1)$$

B. Channel model

We assume the single-input-multiple-output setup, where all BSs transmit unit-power signals with single omnidirectional antenna, while all UEs are equipped with $L$ antenna elements $^1$ [6]–[9]. All wireless links are assumed to experience both small-scale block fading and large-scale path-loss effect. Specifically, we assume that the small-scale fading coefficients follow a Rayleigh distribution. Thus, the channels between each antenna element of the typical UE and the $i$-th BS are denoted as $h_i = [h_{1,i}, h_{2,i}, \ldots, h_{L,i}]$, where $h_{i,j}$ for $i \geq 0$ and $1 \leq j \leq L$, are independent and identically distributed complex Gaussian random variables with zero mean and unit variance. Regarding the large-scale path loss between a transmitter at $X$ and a receiver at $Y$, we adopt an unbounded singular path loss model, i.e. $L(X, Y) = ||X - Y||^\alpha$, where $\alpha > 2$ is the path loss exponent. Hence, the baseband equivalent received signal at the typical UE can be expressed as

$$y = r_0^{-\alpha/2} h_0 s_0 + \sum_{x_i \in \Phi \setminus \{0\}} r_i^{-\alpha/2} h_i s_i + n, \quad (2)$$

where $s_0$ and $s_i$ are the received signals from the serving and the $i$-th interfering BSs, respectively, and $n \in \mathbb{C}^{1 \times L}$ represents additive white Gaussian noise, which is distributed based on $CN(0, \sigma^2 I_L)$.

C. Joint wireless information and power transfer model

We assume that all UEs can decode information and harvest energy simultaneously by using the SWIPT technology, based on either PS or AS schemes. Regarding the scenario where the UE employs the PS scheme, the received RF signal power at each antenna is split into two parts with a ratio $\rho \in [0, 1]$, where a fraction $\rho$ of the signal power is allocated for ID and the other is directed to the rectenna for EH. For the scenario where the UE employs the AS scheme, $\ell$ antennas are used for ID, where $0 \leq \ell \leq L$, and the remaining $L - \ell$ antennas are used for EH [2], [3].

A linear MMSE receiver is assumed to be equipped at each UE, where an optimal weight vector is determined, such that the output SINR is maximized [8], [9]. Hence, the output SINR can be expressed as [9]

$$\gamma = \rho r_0^{-\alpha/2} \tilde{h}_0^H \tilde{R}^{-1} \tilde{h}_0, \quad (3)$$

with

$$\tilde{R} = \sum_{x_i \in \Phi \setminus \{0\}} \rho r_i^{-\alpha/2} \tilde{h}_i \tilde{h}_i^H + \sigma^2 I_{\ell}, \quad (4)$$

where $\tilde{h}_i \leq h_i$ is a $\ell$ dimensional vector representing the channel coefficients of the links between the $i$-th BS and the UE’s antennas allocated for ID. Note that (3) holds for both the PS and AS scheme, i.e. $\ell = L$ and $0 \leq \rho \leq 1$ are adopted for the PS scheme, while $\rho = 1$ and $0 \leq \ell \leq L$ for the AS scheme.

Regarding the energy transfer model, we adopt a practical EH model, which captures the randomness in the detection of the actual harvested energy [12]. More specifically, the harvested energy of a UE is quantified as following [13]

$$\psi = \frac{\nu \eta}{1 + F} \sum_{x_i \in \Phi} \sum_{j=\ell+1}^L h_{ij} r_i^{-\alpha}, \quad (5)$$

where $F$ is an exponential random variable with mean $\zeta$, $\nu = (\zeta e^{\zeta} \int_{-\infty}^{\zeta} e^{-t} t dt)^{-1}$ and $\eta$ is a constant representing the energy conversion efficiency from RF to direct current power. $^1$The consideration of more sophisticated network architectures, e.g. multiple-input-multiple-output setup could be an interesting future work.
III. SWIPT PERFORMANCE WITH A MMSE RECEIVER

In this section, we investigate the ID and the EH performance for scenarios with a MMSE receiver [9]. Firstly, we analytically derive the exact expressions for the ID and the EH success probabilities, by using stochastic geometry tools. Moreover, closed-form expressions of the ID and the EH success probabilities are derived for the interference-limited regime.

A. ID success probability

The ID success probability is defined as the probability that the output SINR of the MMSE receiver is greater than the decoding threshold, \( \beta \), i.e. \( \mathbb{P}[\gamma \geq \beta] \). The achieved ID success probability of the typical UE that employs either the PS or the AS scheme is characterized by the following theorem.

**Theorem 1.** By using a MMSE receiver, the ID success probability of the typical UE is given by

\[
\Pi_1^I(\beta) = \int_0^{\infty} \Gamma\left(\ell, \frac{\alpha}{\sigma^2} r_0^{-1} + 3 \beta r_0^{-1} + \lambda \delta(0, 0)\right) f(r_0) dr_0,
\]

where \( \delta(0, 0) = \frac{2\pi^2 \beta \nu_1}{c^2} \), and \( f(r_0) \) is the pdf of the distance from the typical UE to its serving BS, which is given by (1).

**Proof.** See Appendix A.

Even though the expression in Theorem 1 can be evaluated via numerical tools, this task could be cumbersome due to the complexity of the involved integral. Aiming to further simplify the analysis, we consider special cases with practical interests in the following propositions.

**Proposition 1.** For the interference-limited scenario, where the noise is negligible in comparison to the multi-user interference, the ID success probability of the typical UE is given by

\[
\Pi_1^I(\beta) = 1 - \left(\frac{\alpha - 2}{2\beta^2 \nu_1 (1, \frac{\alpha}{\sigma^2} \frac{\alpha - 2}{2 - \frac{\alpha}{\sigma^2}} - \beta) + 1} \right)^{-\ell},
\]

where \( \tan^{-1}(\cdot) \) is the inverse tangent function.

**Proposition 2.** For the interference-limited scenario with a propagation exponent \( \alpha = 4 \), the ID success probability of the typical UE can be further simplified as

\[
\Pi_1^I(\beta) = 1 - \left(\sqrt{\beta} \tan^{-1}(\sqrt{\beta})^{-1} + 1 \right)^{-\ell},
\]

B. EH success probability

We investigate the EH performance of the typical UE in the context of EH success probability, which is defined as the probability that, the harvested energy of the typical UE is higher than the EH threshold, \( \epsilon \), i.e. \( \mathbb{P}[\psi \geq \epsilon] \). The following theorem provides a closed-form expression for the EH success probability achieved by the typical UE.

**Theorem 2.** The EH success probability of the typical UE is given by

\[
\Pi_1^{E}(\epsilon) = 1 - \exp\left(\frac{\zeta + 2\pi \lambda}{\sqrt{\beta}} \Gamma\left(\frac{\alpha}{\sigma^2}, \frac{\alpha}{\sigma^2} - 1, \frac{\alpha}{\sigma^2} - \beta\right) \right),
\]

where \( s = \frac{\omega n \kappa}{\epsilon} \).

**Proof.** See Appendix C.

From the expression in Theorem 2, we can observe that, if the number of antennas used for EH purpose becomes large (i.e., \( L - \ell \rightarrow \infty \)), the EH success probability approaches one, i.e. \( \lim_{L-\ell \to \infty} \Pi_1^{E}(\epsilon) = 1 \). Furthermore, a denser deployment of the BSs can improve EH performance. Specifically, in the ultra-dense networks with infinite BSs’ density, the EH success probability is equal to one, i.e. \( \lim_{\lambda \to \infty} \Pi_1^{E}(\epsilon) = 1 \).

**Proposition 3.** For the special case with \( \alpha = 4 \), the EH success probability of the typical UE can be further simplified as

\[
\Pi_1^{E}(\epsilon) = 1 - \exp\left(\frac{\zeta - \frac{\pi^2 \sqrt{\beta}}{4L-\ell}(2L-\ell-1)!/(L-\ell)!}{\sqrt{\beta}} \right).
\]

**Proof.** Based on the expression given in Theorem 2 and the resulting expression \( \Gamma\left(\frac{1}{2} + \nu_1, \frac{1}{2} + \nu_1 - \frac{1}{\alpha} \right) = \frac{(2\nu_1)!}{\Gamma(2\nu_1)} \sqrt{\pi} \), the simplified expression for the EH success probability can be obtained.

IV. SUCCESSIVE INTERFERENCE CANCELLATION

In this section, a SIC technique is investigated to improve the ID performance of UEs, via mitigating the strongest interfering signals. The achieved additional gains of the ID performance, release the number of antennas required for ID purpose, which can be used to further enhance the EH performance. In particular, we assume that each UE has the ability to implement an ideal SIC in accordance to [10]. More specifically, the SIC is utilized when the UE fails to decode the intended signal, and tries to decode and subtract the strongest interfering signal from the received signals. If it is successfully decoded, the received signals are re-combined by the MMSE receiver and the UE re-attempts to decode the intended signal. If it still fails to decode the intended signal, it proceeds to decode and subtract the next strongest interfering signal. We consider that the above procedure repeats up to \( N \) times, during which the UE will either successfully decode the intended signal or will be in outage. In addition, the order statistics of the received signal power are assumed to be determined by the distance. In what follows, the observed interference terms from different BSs are assumed to be mutually independent [10].

We start by calculating the probability of the typical UE to successfully decode and subtract the i-th strongest interfering...
The typical UE to its serving BS and the interfering BS, which is given by (1)

Given that $i$ strongest interfering signals have been successfully decoded and subtracted, the ID success probability of the typical UE is characterized in the following Lemma.

**Lemma 1.** By using a MMSE receiver, the probability of the typical UE to successfully decode and subtract the $i$-th strongest interfering signal is given by

$$
\Pi^D(\beta, i) = \int_0^\infty \frac{\Gamma(\ell, \sigma^2 \rho^{-1} \beta r_i^\alpha + \lambda \delta(r_i, \beta))}{\Gamma(\ell)} f(r_i) dr_i,
$$

where $\delta(r_i, \beta) = \frac{2\pi r_i^2 \beta^2 \Gamma(1, \frac{\alpha - \frac{\alpha - 2}{2} \rho^2 \gamma^2}{\alpha - 2})}{\alpha - 2}$ and $f(r_i)$ is the pdf of the distance between the typical UE and the $i$-th closest interfering BS, which is given by (1).

**Proof.** See Appendix D.

We now present the main theorem for the ID success probability of the typical UE, by taking into account both the MMSE receiver and the SIC technique.

**Theorem 3.** By using a MMSE receiver, the ID success probability of the typical UE which attempts to cancel up to $N$ interfering signals is given by

$$
\Pi^{\text{SIC}}(\beta, N) = \Pi^D(\beta) + \sum_{j=1}^N \left( \prod_{i=0}^{j-1} 1 - \Pi^C(\beta, i) \right) \left( \prod_{i=1}^{j} \Pi^D(\beta, i) \right) \Pi^C(\beta, i).
$$

**Proof.** For the sake of the analytical tractability, we assume that the interfering signals are independent. Therefore, the proof is directly given from the SIC procedure.
it can be observed that a larger number of antennas or a larger power splitting ratio achieve a higher ID success probability. This was expected since, for the AS scheme, by allocating more antennas for ID purpose, a greater output SINR is achieved of the MMSE receiver. In addition, for the PS scheme, by allocating more signal power for ID purpose, noise effects are suppressed accordingly, thereby improving the ID performance of UEs. Another interesting observation is that, based on either the AS or the PS scheme, by allocating half number of the total antennas \((\ell = 4)\) or half total received signal power \((\rho = 0.5)\) for ID purpose, the PS scheme outperforms the AS scheme in terms of ID success probability. This observation is justified from the fact that the AS scheme randomly selects part of antennas for ID, which may have a poor signal quality (i.e. low SINR); while PS scheme utilizes all receiving antennas, which enables the best diversity branches to be combined, thus resulting in a better ID performance. Finally, we can observe that, with denser network deployments \((\lambda = 0.001)\), the interference limited scenario \((\text{given in Proposition 1})\) provides a tight approximation with the exact ID success probability.

Fig. 2 depicts the impact of the AS and the PS schemes on the EH success probability (given in Theorem 2 and Proposition 3) for different densities of the BSs, i.e. \(\lambda \in \{1/3000, 1/1000\}\). Firstly, it can be observed that, a denser deployment of BSs achieves a higher EH success probability. This was expected since, a denser network provides more multi-user interference, which can be used for harvesting energy by the UEs. We can also observe that, by allocating more antennas or more signal power for EH purpose, the EH performance is improved. Finally, it is indicated that, for the case where the half received power or half number of antennas are allocated for EH based on the PS and AS scheme, respectively, the PS scheme achieves a slightly higher EH success probability than the AS scheme.

Fig. 3 shows the achieved ID and EH success probability regions, with different number of receiving antennas \(L \in \{4, 8, 16\}\) and with different techniques, i.e. MRC receiver, MMSE receiver, and MMSE receiver with the SIC technique (denoted as MMSE-SIC), where the AS scheme is employed and the noise power is ignored. Firstly, a clear trade-off between the ID and the EH performance can be observed for any number of receiving antennas. This was expected since, by allocating more number of antennas for ID (or EH) purpose, the corresponding performance is improved, while on the other hand, the EH (or ID) success probability is decreased since less resources are allocated. Similarly, by increasing the total number of antennas, both the ID and the EH performance is improved. Moreover, Fig. 3 plots the performance achieved by the MRC technique for comparison purpose [6]. We can observe that, the MMSE outperforms the MRC for any number of antennas. This is based on the fact that the MMSE receiver is an optimal combining approach, which yields a maximum output SINR, while the MRC receiver is a low-complexity approach and achieves a worse performance when the interference signals are correlated. Finally, an addition gain can be observed with the employment of the MMSE-SIC technique. In this case, the strongest interfering signals are decoded and subtracted, resulting in a higher SINR, thereby the ID success probability is increased.

VI. Conclusion

In this paper, we studied the SWIPT technology in the context of a linear MMSE receiver. By leveraging tools from stochastic geometry, we established a tractable mathematical framework to evaluate the SWIPT performance for multiple antennas UEs. Based on PS or AS schemes, exact analytical expressions for both the ID and the EH success probabilities were derived, while simple closed-form expressions were obtained for the interference-limited case. Moreover, a SIC technique was investigated to further improve the SWIPT performance, via mitigating the strongest interfering signals. Our results have shown that, the MMSE receiver outperforms the conventional MRC in terms of SWIPT performance. By using a MMSE receiver and by allocating an equal fraction of resources for ID and EH, the PS scheme outperforms the AS in the context of both the ID and the EH performance. Finally, by employing the SIC technique, an additional gain on SWIPT performance was demonstrated in terms of both the ID and the EH success probabilities performance.

APPENDIX A

PROOF OF THEOREM 1

Firstly, by conditioning on the distance between the typical UE to all BSs, the conditional ID success probability could be formulated as [8]

\[
\mathbb{P}[\gamma \geq \beta | r_0, r_1, \ldots, r_K] = \frac{\exp \left(\frac{-\sigma^2 \beta r_0^\alpha}{\rho} \sum_{j=0}^{\ell-1} a_i(\beta r_0)^i \right)}{\prod_{j=1}^{K} (1 + r_j^{-\alpha} \beta r_0)^i},
\]

where \(K\) is the number of BSs, and \(a_i\) are the first \(\ell\) coefficient of the Taylor expansion of \(\exp \left(\frac{-\sigma^2 \beta r_0^\alpha}{\rho} \sum_{j=1}^{K} (1 + r_j^{-\alpha} \beta r_0)^i\right)\).

Then, by un-conditioning over the distance from the typical UE to interfering BSs, i.e. \(r_1, r_2, \ldots, r_K\), and following [9, Eq. (15)], the conditional ID success probability, i.e. \(\mathbb{P}[\gamma \geq \beta | r_0]\) can be expressed as

\[
\mathbb{P}[\gamma \geq \beta | r_0] = \exp \left(\frac{-\sigma^2 \beta r_0^\alpha}{\rho} \sum_{j=0}^{\ell-1} \frac{a_i(\beta r_0)^i}{k!(j-k)!} \right) \times \left(2\pi \lambda \int_{r_0}^{\infty} \frac{x^{1-\alpha} \beta r_0^\alpha}{1 + x^{-\alpha} \beta r_0^\alpha} dx \right) ^{k} \times \exp \left(\frac{2\pi \lambda}{\rho} \int_{r_0}^{\infty} \frac{1}{1 + x^{-\alpha} \beta r_0^\alpha} dx \right).
\]

The above integrals can be evaluated, by using the transformation \(u \leftarrow x^2\) and by using the expression in [15, 3.24], such that we have

\[
\mathbb{P}[\gamma \geq \beta | r_0] = \exp \left(\frac{-\sigma^2 \beta r_0^\alpha}{\rho} \sum_{j=0}^{\ell-1} \frac{a_i(\beta r_0)^i}{k!(j-k)!} \right) \times \left(\lambda \delta(r_0, \beta)\right)^{k} \exp \left(\frac{-\lambda \delta(r_0, \beta)}{\rho}\right),
\]
where \( \delta(r_0, \beta) = \frac{2\pi^2 a_d}{f_1(\frac{a_n^2 - a}{a - 2})} \). Then, by using the binomial theorem [16], the above expression can be further reconstructed as

\[
P[\gamma \geq \beta | \rho_0] = \exp \left( -\frac{\rho \lambda \delta(r_0, \beta) + \beta \rho_0^2 \sigma^2}{\rho} \right) \frac{\rho}{\rho_0} \sum_{j=0}^{\ell-1} \frac{(\sigma^2 \rho^{-1} \beta \rho_0^2 + \lambda \delta(r_0, \beta))^j}{j!}
\]

where the final step is based on the expression in [17, Eq(6.89)]. Finally, by un-conditioning with respect to \( r_0 \), the result in Theorem 1 can be obtained.

**APPENDIX B**

**Proof of Proposition 1**

Based on the expression obtained in Theorem 1, the ID success probability for the interference-limited scenario, where the additive noise is neglected, can be derived by utilizing the transformation \( x \leftarrow \delta(r_0, \beta) \), which yields

\[
\Pi^I(\beta) = \int_0^\infty \frac{\Gamma(\ell, x)}{\Gamma(\ell)} \exp \left( -\frac{x(\alpha - 2)}{2\beta y} \right) \frac{\alpha - 2}{2\beta y} dx,
\]

where \( y = 2F_1(1, \frac{a_n^2 - 2}{a - 1}, -\beta) \). Then, by using the resulting expression [15, 6.451], the desired expression can be obtained.

**APPENDIX C**

**Proof of Theorem 2**

The EH success probability can be re-written as

\[
P[\psi \geq \epsilon] = P \left[ \frac{\nu_\rho}{\epsilon} \sum_{\ell=1}^L \sum_{j=0}^{h_{ji}} |h_{ji}|^2 \gamma_i - \alpha - 1 \right].
\]

Since \( F \) is an exponential random variable with mean \( \zeta \), the above equation can be expressed as

\[
P[\psi \geq \epsilon] = 1 - \exp \left( \prod_{\ell=1}^L \exp \left( -\frac{\nu_\rho \zeta c_i}{\epsilon \gamma_i} \right) \right) \exp(\zeta),
\]

where \( c_i = \sum_{j=0}^{h_{ji}} |h_{ji}|^2 \). Since for the Rayleigh fading, the channel power gain is an exponential random variable, i.e. \( |h_{ji}|^2 \sim \exp(1) \), \( c_i \) is a Gamma distributed random variable with shape parameter \( L - \ell \) and unit scale, i.e. \( c_i \sim \mathcal{G}(L - \ell, 1) \) [6]. Therefore, the above expectations can be evaluated as follows

\[
E \left[ \prod_{x_i, \in \Phi} \int_0^\infty \exp \left( -\frac{\nu_\rho \zeta c_i}{\epsilon \gamma_i} \right) \frac{\exp(-c) c^{L-\ell-1}}{\Gamma(L-\ell)} dc \right] \quad (a) = \prod_{x_i, \in \Phi} \left( \frac{e^{\epsilon \gamma_i}}{\nu_\rho \zeta + e^{\epsilon \gamma_i}} \right)^{L-\ell} \quad (b) \exp \left( -2\pi \lambda \int_0^\infty \left( 1 - \left( \frac{e^{\epsilon \gamma_i}}{\nu_\rho \zeta + e^{\epsilon \gamma_i}} \right)^{L-\ell} \right) r dr \right)
\]

where (a) is derived based on the resulting expression [15, 3.351] and (b) follows from the probability generating functional of a PPP [11]. Finally, by evaluating the above integral and by substituting (16) into (15), the final result in Theorem 2 is derived.

**APPENDIX D**

**Proof of Lemma 1**

Since the \( i - 1 \) interfering signals are assumed to be already subtracted, the remaining interferers set is \( \tilde{\Phi} = \{ x_{i+1}, x_{i+2}, \cdots \} \) and the \( i \)-th interfering signal is now treated as the intended signal to be decoded. Hence, the output SINR of the MMSE receiver is given by

\[
\gamma_i = \rho_\epsilon^{-\alpha} \hat{h}_i^T R^{-1} \hat{h}_i,
\]

where \( R = \sum_{x_i \in \tilde{\Phi}} \rho_\epsilon^{-\alpha} \hat{h}_i^T \hat{h}_i + \sigma^2 I_r \) denotes the covariance matrix of the interference plus noise. Then the proof follows similar methodology with Appendix A, i.e. first conditioning on \( r_i \) and replacing the integral limits \( r_0 \) with \( r_i \), then evaluating the expectation over \( r_i \).

**REFERENCES**

[1] T. Huang, W. Yang, J. Wu, I. Ma, X. Zhang, and D. Zhang, “A survey on green 6G network: Architecture and technologies,” IEEE Access, vol. 7, pp. 175758–175768, Dec. 2019.
[2] I. Krikidis, S. Timotheou, S. Nikolau, G. Zheng, D. W. K. Ng, and R. Schober, “Simultaneous wireless information and power transfer in modern communication systems,” IEEE Commun. Mag., vol. 52, no. 11, pp. 104–110, Nov. 2014.
[3] R. Zhang and C. K. Ho, “MIMO broadcasting for simultaneous wireless information and power transfer,” IEEE Trans. Wireless Commun., vol. 12, no. 5, pp. 1989–2001, May 2013.
[4] Q. Wu and R. Zhang, “Weighted sum power maximization for intelligent reflecting surface aided SWIFT,” IEEE Commun. Lett., vol. 9, no. 5, pp. 586–590, May 2020.
[5] M. Di Renzo and W. Lu, “System-level analysis and optimization of cellular networks with simultaneous wireless information and power transfer: Stochastic geometry modeling,” IEEE Trans. Veh. Technol., vol. 66, no. 3, pp. 2251–2275, Mar. 2017.
[6] R. Tanbourgi, H. S. Dhillon, J. G. Andrews, and F. K. Jondral, “Effect of spatial interference correlation on the performance of maximum ratio combining,” IEEE Trans. Commun., vol. 13, no. 6, pp. 3307–3316, Jun. 2014.
[7] Y. Wang, F. Liu, C. Wang, P. Wang, and Y. Ji, “Outage probability of SIMO MRC receivers with correlated poisson field of interferers,” IEEE Commun. Lett., vol. 25, no. 1, pp. 74–78, Jan. 2021.
[8] H. Gao, P. Smith, and M. Clark, “Theoretical reliability of MMSE linear diversity combining in Rayleigh-fading additive interference channels,” IEEE Trans. Commun., vol. 46, no. 5, pp. 666–672, May 1998.
[9] O. B. S. Ali, C. Cardinal, and F. Gagnon, “Performance of optimum combining in a Poisson field of interferers and Rayleigh fading channels,” IEEE Trans. Wireless Commun., vol. 9, no. 8, pp. 2461–2467, Aug. 2010.
[10] M. Wilde, “Successive interference cancellation in heterogeneous networks,” IEEE Trans. Commun., vol. 62, no. 12, pp. 4440–4453, Jun. 2014.
[11] M. Haenggi, Stochastic Geometry for Wireless Networks. Cambridge University Press, 2012.
[12] X. Lu, I. Flint, D. Niyato, N. Privault, and P. Wang, “Self-sustainable communications with RF energy harvesting: Ginibre point process modeling and analysis,” IEEE J. Sel. Areas Commun., vol. 34, no. 5, pp. 1518–1535, Apr. 2016.
[13] N. Deng and M. Haenggi, “The energy and rate meta distributions in wirelessly powered D2D networks,” IEEE J. Sel. Areas Commun., vol. 37, no. 2, pp. 269–282, Sep. 2019.
[14] S. T. Veeft, K. Kuchibhotla, and K. K. Ganti, “Performance of PZF and MMSE receivers in cellular networks with multi-user spatial multiplexing,” IEEE Trans. Wireless Commun., vol. 14, no. 9, pp. 4867–4878, Sep. 2015.
[15] I. S. Gradshteyn and I. M. Ryzhik, Table of integrals, series, and products. Elsevier, 2007.
[16] G. Upton and I. Cook, A Dictionary of Statistics. OUP Oxford, 2008.
[17] G. B. Arfken and H. J. Weber, Mathematical methods for physicists, 6th ed. Elsevier, 2005.