Probability of Strictly Positive Secrecy Capacity of the Weibull Fading Channel

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***Abstract*: In this paper, the information-theoretic secrecy of Weibull fading channels is investigated. The present work generalizes the analysis on Rayleigh fading. Several formulas of the probability of strictly positive secrecy capacity are derived. It is shown that in some cases the results can be expressed in terms of a general function, the Meijer G-function. Profile examples are illustrated and discussed.**

Keywords: Information-theoretic secrecy, secrecy capacity, Weibull fading.

I. INTRODUCTION

Recently, there was an ever increasing interest of exploring the *secrecy capacity* (SC) in digital communications over fading channels. In [1-2], the authors investigated the Rayleigh SC with various scenarios. The discussion of Nakagami-m SC can be found in [3]. The studies on the log-normal SC were reported in [4]. There was also an analysis on the Rician SC [5]. However, to the author's best knowledge, the Weibull SC has not been addressed in the literature. An effort is made to fill this gap in the present work.

In wireless communications, the Weibull model has been used to describe the fading induced by multipath propagations, usually for indoor radio systems and sometimes also for outdoor radio systems. Extensive experiments and simulations have been reported in the literature (see [6-9] and the references therein). Note that the Weibull fading includes the well-known Rayleigh fading and exponential fading as special cases.

The rest of this paper is organized as follows. In Section II, the notion of SC is introduced and the probability of *strictly positive secrecy capacity* (SPSC) of the concerned system is derived. Next, in Section III, the behavior of SPSC is discussed and several closed-form formulas are derived. Then, the outage probability assessment is discussed in Section IV. Finally, the conclusion is included in Section V.

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II. SYSTEM MODEL AND SECRECY CAPACITY

The concept of SC is based on the notion of information-theoretic secrecy (ITS) [10-12]. In the context of SC analysis, the communication system is usually abstracted by three entities: a legitimate transmitter (Alice), a legitimate receiver (Bob), and an eavesdropper. When Alice sends information to Bob, the eavesdropper can intercept the information (Fig. 1).

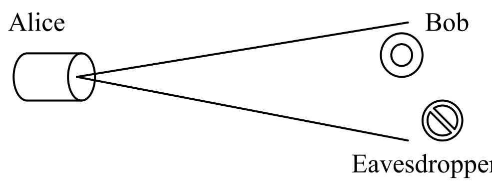

Figure 1. System model.

The eavesdropper is assumed to be purely passive and malicious. Under this assumption, no *channel state information* (CSI) of the eavesdropper is available for Alice. Consider the path *signal-to-noise ratio* (SNR) per symbol. Let the instantaneous SNR of Bob and the eavesdropper be U and W, respectively.

In the case of Weibull fading, the *probability density function* (PDF) of U takes the following form [13, eq. (2.29)]:

$$f_U(u) = \frac{a}{2}\left[\frac{1}{u_0}\Gamma\left(1+\frac{2}{a}\right)\right]^{a/2} u^{(a/2)-1} \exp\left(-\left[\frac{u}{u_0}\Gamma\left(1+\frac{2}{a}\right)\right]^{\frac{a}{2}}\right), \quad (u \geq 0,\ a > 0) \qquad (1)$$

where a is the fading factor of the main channel, u_0 is the mean of U, and $\Gamma(\bullet)$ is the gamma function, defined as:

$$\Gamma(x) = \int_0^\infty t^{x-1}\exp(-t)dt.$$

In general, the fading gets severer as the factor a decreases [13, Sec. 2.2.1.5]. Note that, when $a = 2$, the Weibull distribution reduces to the well-known exponential distribution. Similarly, for the eavesdropper channel, the PDF of W is:

$$f_W(w) = \frac{b}{2}\left[\frac{1}{w_0}\Gamma\left(1+\frac{2}{b}\right)\right]^{b/2} w^{(b/2)-1} \exp\left(-\left[\frac{w}{w_0}\Gamma\left(1+\frac{2}{b}\right)\right]^{\frac{b}{2}}\right),$$
$$(w \geq 0,\ b > 0) \qquad (2)$$

where b is the fading factor of the eavesdropper channel and w_0 is the mean of W. Corresponding to (1) and (2), the *cumulative probability functions* (CDFs) take the following form:

$$F_U(u) = 1 - \exp\left(-\left[\frac{u}{u_0}\Gamma\left(1+\frac{2}{a}\right)\right]^{a/2}\right), \qquad (3)$$

$$F_W(w) = 1 - \exp\left(-\left[\frac{w}{w_0}\Gamma\left(1+\frac{2}{b}\right)\right]^{b/2}\right). \qquad (4)$$

In the present work, the analysis is based on the notion described in [2, Lemma 1], where the SC for one realization of the SNR pair (U,W) of the quasi-static complex fading wiretap-channel is expressed as:

$$C_s = \begin{cases} \log_2(1+U) - \log_2(1+W), & (U > W) \\ 0. & (U \leq W) \end{cases} \qquad (5)$$

Note that the SC C_s given in (5) is a random variable. Consequently, with a target transmission rate τ specified, the *complementary outage probability* (CPOP) of SC can be evaluated by

$$P_h = \Pr(C_s > \tau) = \Pr\left(\log_2\frac{1+U}{1+W} > \tau\right)$$
$$= \Pr\left(\ln\frac{1+U}{1+W} > h\right), \qquad (6)$$

where $h = \tau \ln 2$. In secure communications, the probability of strictly positive secrecy capacity (SPSC) is a fundamental benchmark. This probability can be obtained by setting $h = 0$ in (6):

$$P_0 = \Pr\left(\ln\frac{1+U}{1+W} > 0\right) = \Pr(U > W). \qquad (7)$$

Let $Z = U/W$. Then the evaluation of (7) is equivalent to the analysis on the distribution function of Z. The PDF of Z can be expressed as follows:

$$f_Z(z) = \int_0^\infty w f_U(wz) f_W(w) dw. \qquad (8)$$

Accordingly, the CDF of Z can be formulated as follows:

$$F_Z(z) = \int_0^z f_Z(t)dt = \int_0^z \int_0^\infty w f_U(wt) f_W(w) dw dt$$
$$= \int_0^\infty f_W(w)\left[\int_0^{wz} f_U(y)dy\right]dw = \int_0^\infty f_W(w) F_U(wz) dw. \qquad (9)$$

Substituting (2) and (3) into (9), with several transformations, we obtain:

$$F_Z(z) = \frac{b}{2}(H_1 - H_2), \qquad (10)$$

where

$$H_1 = \int_0^\infty w^{(b/2)-1}\left[\frac{1}{w_0}\Gamma\left(1+\frac{2}{b}\right)\right]^{\frac{b}{2}}$$
$$\times \exp\left(-\left[\frac{w}{w_0}\Gamma\left(1+\frac{2}{b}\right)\right]^{\frac{b}{2}}\right)dw = \frac{2}{b}, \qquad (11)$$

$$H_2 = \int_0^\infty w^{(b/2)-1}\left[\exp\left(-\left[\frac{wz}{u_0}\Gamma\left(1+\frac{2}{a}\right)\right]^{\frac{a}{2}}\right)\right]$$
$$\times\left[\frac{1}{w_0}\Gamma\left(1+\frac{2}{b}\right)\right]^{\frac{b}{2}} \exp\left(-\left[\frac{w}{w_0}\Gamma\left(1+\frac{2}{b}\right)\right]^{\frac{b}{2}}\right)dw$$
$$= \left(\frac{2}{b}\right)\int_0^\infty \exp\left[-t - \left(\frac{b\Gamma(2/a)z}{a\Gamma(2/b)r}\right)^{\frac{a}{2}} t^{a/b}\right]dt, \qquad (12)$$

and

$$r = u_0 / w_0. \qquad (13)$$

In the derivation of (12), the following identity was incorporated [14, eq. (8.331.1)]:

$$\Gamma(x+1) = x\Gamma(x). \qquad (14)$$

Substituting (11) and (12) into (10), we have:

$$F_Z(z) = 1 - \int_0^\infty \exp\left[-t - \left(\frac{b\Gamma(2/a)z}{a\Gamma(2/b)r}\right)^{\frac{a}{2}} t^{a/b}\right]dt. \qquad (15)$$

Accordingly,

$$P_0 = 1 - F_Z(1)$$
$$= \int_0^\infty \exp\left[-t - \left(\frac{b\Gamma(2/a)}{a\Gamma(2/b)r}\right)^{\frac{a}{2}} t^{a/b}\right]dt. \qquad (16)$$

As a general formula, eq. (16) can be used to evaluate the SPSC for a realization of U and W with arbitrary fading parameters a and b. Three sets of sample data of P_0 are presented in Tables I to III. The corresponding profiles are illustrated in Figs. 2 to 4.

TABLE I. SAMPLE DATA OF P_0 $(r = 0.5)$

$b \backslash a$	1	2	3	4
1	0.4142	0.5456	0.5864	0.6039
2	0.2421	0.3333	0.3615	0.3735
3	0.1906	0.2506	0.2612	0.2630

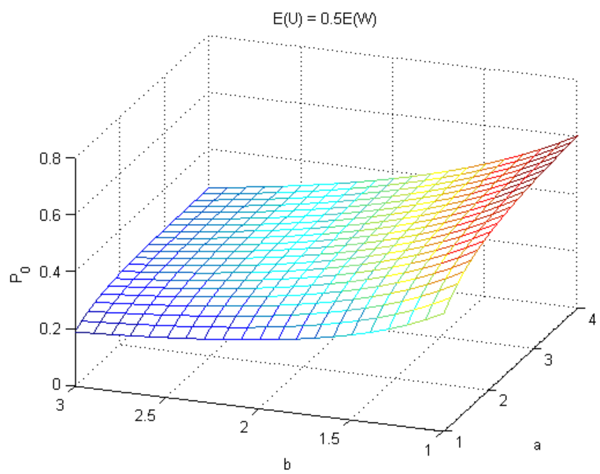

Figure 2. Profile example 1 of SPSC.

TABLE II. SAMPLE DATA OF P_0 $(r = 1)$

$b \backslash a$	1	2	3	4
1	0.5000	0.6557	0.7036	0.7242
2	0.3443	0.5000	0.5574	0.5842
3	0.2964	0.4426	0.5000	0.5272

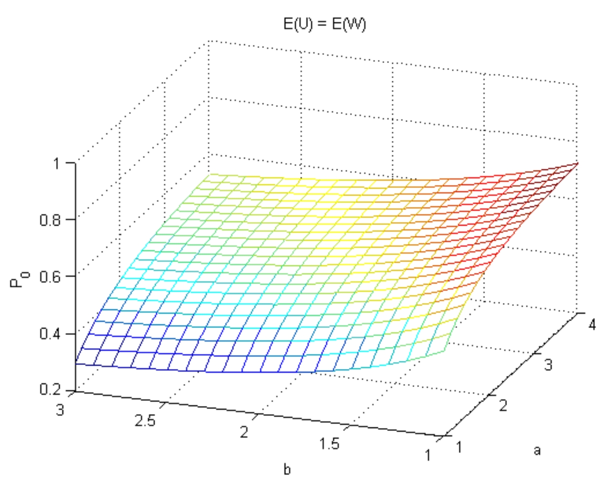

Figure 3. Profile example 2 of SPSC.

TABLE III. SAMPLE DATA OF P_0 $(r = 2)$

$b \backslash a$	1	2	3	4
1	0.5858	0.7579	0.8094	0.8311
2	0.4544	0.6667	0.7494	0.7898
3	0.4136	0.6385	0.7388	0.7928

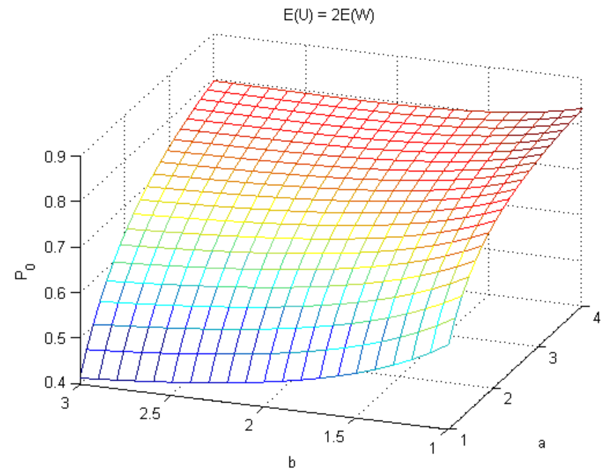

Figure 4. Profile example 3 of SPSC.

III. SOME REMARKS

Several important insights can be gained from the profiles illustrated in Figs. 2 and 4. First, the SPSC is favored by increasing r, the ratio of $E(U)$ to $E(W)$. Secondly, the SPSC is favored with the ascending values of a, the main channel's fading factor. This is expected since a larger value of a describes less fading of the main channel. Thirdly, the SPSC is favored with the descending values of b, the eavesdropper channel's fading factor. This is also expected since a smaller value of b describes more fading of the eavesdropper channel.

We can also look at the performance from a different aspect by continuously varying the parameter r, with fixed fading factors. As a matter of fact, we are able to derive several closed-form formulas of P_0, as shown below.

- Case 1: $b = a$.

In this case, eq. (15) becomes

$$F_Z(z) = 1 - \int_0^\infty \exp\left[-t - \left(\frac{z}{r}\right)^{\frac{a}{2}} t\right] dt = 1 - \frac{1}{1+(z/r)^{a/2}}. \quad (17)$$

Consequently,

$$P_0 = 1 - F_Z(1) = \frac{1}{1+(1/r)^{a/2}} = \frac{r^{a/2}}{1+r^{a/2}}. \tag{18}$$

The profile of (18) is illustrated in Fig. 5. Note that when $a=2$ the Weibull distribution reduces to the exponential distribution for SNR (i.e., the Rayleigh distribution for envelope) and (18) becomes

$$P_0 = \frac{r}{1+r}. \tag{19}$$

Thus eq. (18) includes the result reported in [2] (eq. (7) as a special case.

TABLE IV. SAMPLE DATA OF P_0 $(b=a)$

$r \setminus a$	1	2	3	4
0.5	0.4142	0.3333	0.2612	0.2000
1.0	0.5000	0.5000	0.5000	0.5000
1.5	0.5505	0.6000	0.6475	0.6923
2.0	0.5858	0.6667	0.7388	0.8000
2.5	0.6126	0.7143	0.7981	0.8621
3.0	0.6340	0.7500	0.8386	0.9000

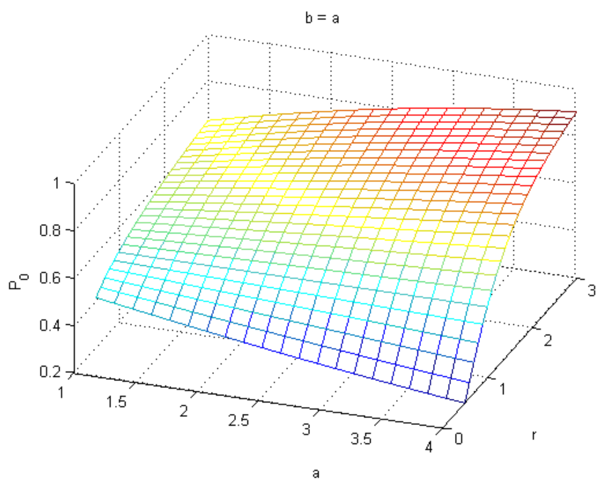

Figure 5. Profile example 4 of SPSC.

- Case 2: $a = 2b$.

In this case, eq. (15) becomes

$$F_Z(z) = 1 - \int_0^\infty \exp\left[-t - \left(\frac{b\Gamma(2/a)z}{a\Gamma(2/b)r}\right)^{\frac{a}{2}} t^{a/b}\right] dt$$

$$= 1 - \int_0^\infty \exp\left[-t - \left(\frac{\Gamma(2/a)z}{2\Gamma(4/a)r}\right)^{\frac{a}{2}} t^2\right] dt. \tag{20}$$

According to the identity presented in [14, p. 336, eq. (3.322.2)] or [15, p. 146, eq. (21)], with several variable conversions, we obtain:

$$F(z) = 1 - \sqrt{\pi}\left(\frac{2\Gamma(4/a)r}{\Gamma(2/a)z}\right)^{a/4} \times \exp\left[\frac{1}{4}\left(\frac{2\Gamma(4/a)r}{\Gamma(2/a)z}\right)^{a/2}\right] Q\left[\frac{1}{\sqrt{2}}\left(\frac{2\Gamma(4/a)r}{\Gamma(2/a)z}\right)^{a/4}\right], \tag{21}$$

where $Q(\bullet)$ is the *Gaussian* Q-function, defined as:

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty \exp\left(-\frac{t^2}{2}\right) dt. \tag{22}$$

Consequently,

$$P_0 = 1 - F_Z(1) = \sqrt{\pi}\left(\frac{2\Gamma(4/a)r}{\Gamma(2/a)}\right)^{a/4} \times \exp\left[\frac{1}{4}\left(\frac{2\Gamma(4/a)r}{\Gamma(2/a)}\right)^{a/2}\right] Q\left[\frac{1}{\sqrt{2}}\left(\frac{2\Gamma(4/a)r}{\Gamma(2/a)}\right)^{a/4}\right]. \tag{23}$$

When the main channel is exponential for SNR (i.e., Rayleigh for envelope), characterized by $a=2$, eq. (23) becomes:

$$P_0 = \sqrt{2\pi r}\exp\left(\frac{r}{2}\right) Q\left(\sqrt{r}\right). \tag{24}$$

- Case 3: $b = 2a$.

In this case, eq. (15) becomes

$$F_Z(z) = 1 - \int_0^\infty \exp\left[-t - \left(\frac{2\Gamma(2/a)z}{\Gamma(1/a)r}\right)^{\frac{a}{2}} t^{1/2}\right] dt. \tag{25}$$

According to the identity presented in [15, p. 146, eq. (31)], with several variable conversions, we obtain:

$$F(z) = p\sqrt{\pi}\exp\left(\frac{p^2}{4}\right) Q\left(\frac{p\sqrt{2}}{2}\right)$$

$$= \left[\frac{2\Gamma(2/a)z}{\Gamma(1/a)r}\right]^{a/2} \sqrt{\pi}\exp\left(\frac{1}{4}\left[\frac{2\Gamma(2/a)z}{\Gamma(1/a)r}\right]^a\right) \times Q\left(\frac{\sqrt{2}}{2}\left[\frac{2\Gamma(2/a)z}{\Gamma(1/a)r}\right]^{a/2}\right). \tag{26}$$

Consequently,

$$P_0 = 1 - F_Z(1)$$

$$= 1 - \sqrt{\pi}\left[\frac{2\Gamma(2/a)}{\Gamma(1/a)r}\right]^{a/2} \exp\left(\frac{1}{4}\left[\frac{2\Gamma(2/a)}{\Gamma(1/a)r}\right]^a\right) \times Q\left(\frac{\sqrt{2}}{2}\left[\frac{2\Gamma(2/a)}{\Gamma(1/a)r}\right]^{a/2}\right). \tag{27}$$

When the main channel is exponential for SNR (i.e., Rayleigh for envelope), characterized by $a = 2$, eq. (27) becomes:

$$P_0 = 1 - \left(\frac{2}{r}\right) \exp\left(\frac{1}{\pi r^2}\right) Q\left(\frac{\sqrt{2}}{r\sqrt{\pi}}\right). \tag{28}$$

In the following, we discuses two general cases.

- Case 4: $a = kb$, where k is a positive integer.

In this case, eq. (15) becomes:

$$F_Z(z) = 1 - \int_0^\infty \exp\left[-t - \left(\frac{\Gamma(2/a)z}{k\Gamma(2k/a)r}\right)^{\frac{a}{2}} t^k\right] dt. \tag{29}$$

In [9], the following result was reported:

$$\int_0^\infty x^{p-1} \exp\left(-\alpha x^k - \beta x\right) dx = (2\pi)^{(1-k)/2} k^{p-(1/2)} \beta^{-p} \times G_{1,k}^{k,1}\left(\frac{\beta^k}{\alpha k^k} \left| \begin{matrix} 1 \\ \frac{p}{k}, \frac{p+1}{k}, \ldots, \frac{p+k-1}{k} \end{matrix}\right.\right), \tag{30}$$

where $p > 0$, $a > 0$, $\beta > 0$, k is a positive integer, and $G_{p,q}^{m,n}$ is the *Meijer G*-function [14, Sec. 9.3]. Accordingly, eq. (29) can be converted to:

$$F_Z(z) = 1 - (2\pi)^{(1-k)/2} \sqrt{k} \times G_{1,k}^{k,1}\left(\left[\frac{k\Gamma(2k/a)r}{\Gamma(2/a)z}\right]^{\frac{a}{2}} \frac{1}{k^k} \left| \begin{matrix} 1 \\ \frac{1}{k}, \frac{2}{k}, \ldots, 1 \end{matrix}\right.\right). \tag{31}$$

Incorporating (31), we have:

$$P_0 = 1 - F_Z(1) = (2\pi)^{(1-k)/2} \sqrt{k} \times G_{1,k}^{k,1}\left(\left[\frac{k\Gamma(2k/a)r}{\Gamma(2/a)}\right]^{\frac{a}{2}} \frac{1}{k^k} \left| \begin{matrix} 1 \\ \frac{1}{k}, \frac{2}{k}, \ldots, 1 \end{matrix}\right.\right). \tag{32}$$

- Case 5: $b = ka$, where k is a positive integer.

In this case, eq. (15) becomes:

$$F_Z(z) = 1 - \int_0^\infty \exp\left[-t - \left(\frac{k\Gamma(2/a)z}{\Gamma(2/(ka))r}\right)^{\frac{a}{2}} t^{1/k}\right] dt. \tag{33}$$

Note that in (33) the exponent of t is not an integer. This type of integral was not addressed in [9]. However, we found a pivotal transform $x = t^{1/k}$ that resolves the integral in (33). First, with $x = t^{1/k}$, eq. (33) becomes:

$$F_Z(z) = 1 - k \int_0^\infty x^{k-1} \exp\left[-x^k - \left(\frac{k\Gamma(2/a)z}{\Gamma(2/(ka))r}\right)^{\frac{a}{2}} x\right] dx. \tag{34}$$

Then, based on eq. (30), eq. (34) can be converted to:

$$F_Z(z) = 1 - (2\pi)^{(1-k)/2} k^{k+(1/2)} \left[\frac{\Gamma(2/(ka))r}{k\Gamma(2/a)z}\right]^{\frac{ak}{2}} \times G_{1,k}^{k,1}\left(\frac{1}{k^k}\left[\frac{k\Gamma(2/a)z}{\Gamma(2/(ka))r}\right]^{\frac{ak}{2}} \left| \begin{matrix} 1 \\ 1, \frac{k+1}{k}, \ldots, \frac{2k-1}{k} \end{matrix}\right.\right). \tag{35}$$

Therefore,

$$P_0 = 1 - F_Z(1) = (2\pi)^{(1-k)/2} k^{k+(1/2)} \left[\frac{\Gamma(2/(ka))r}{k\Gamma(2/a)}\right]^{\frac{ak}{2}} \times G_{1,k}^{k,1}\left(\frac{1}{k^k}\left[\frac{k\Gamma(2/a)z}{\Gamma(2/(ka))r}\right]^{\frac{ak}{2}} \left| \begin{matrix} 1 \\ 1, \frac{k+1}{k}, \ldots, \frac{2k-1}{k} \end{matrix}\right.\right). \tag{36}$$

In the preceding discussions, the first three cases can be regarded as special cases of Case 4 or Case 5. However, since eq. (32) or (36) is expressed in terms of the Meijer G-function, it is more convenient to implement the formulas based on basic functions, such as eqs. (18), (23), and (27), in Matlab. It should be mentioned that, in Cases 4 and 5, k needs to be a positive integer. For the case of k being not a positive integer, no any closed-form formula has been reported in the literature yet. Eq. (16) seems to be the only means to handle the most general case.

IV. A Lower Bound of the Outage Probability

Although this paper focuses on SPSC, the core formulas derived in the preceding sections can also serve the needs of assessing the *outage probability* (OP). In the literature of SC [2], the OP is usually defined as follows:

$$P_{out}(R_s) = \Pr(C_s \le R_s), \tag{37}$$

where $R_s > 0$ is the pre-specified secrecy rate. Substituting (5) into (37), we have:

$$\begin{aligned} P_{out}(R_s) &= \Pr\left[\log_2\left(\frac{1+U}{1+W}\right) \le R_s\right] \quad (U > W) \\ &= \Pr\left(\frac{1+U}{1+W} \le 2^{R_s}\right) = \Pr\left(U \le 2^{R_s} W + 2^{R_s} - 1\right) \\ &> \Pr\left(U \le 2^{R_s} W\right) = \Pr\left(\frac{U}{W} \le 2^{R_s}\right) \\ &= \Pr\left(Z \le 2^{R_s}\right) = F_Z\left(2^{R_s}\right). \end{aligned} \tag{38}$$

Note that, in the derivation process of (38) above, we used the fact of $2^{R_s} > 1$ because $R_s > 0$, and the definition of Z introduced in (8) before. Therefore, in (38) the entity $F_Z(2^{R_s})$ provides a lower bound for the OP. Consequently, depending on the cases, eqs. (15), (17), (21), (26), (31), and (35) can be used to evaluate the lower bound of OP.

V. CONCLUSION

The Weibull distribution characterizes the fading induced by multipath propagations occurred in the mobile radio systems. In secure communications, the probability of strictly positive secrecy capacity is a fundamental benchmark. This paper investigates the behavior of SPSC in the environment of Weibull fading. A general formula is derived first. Then it is refined to the closed-form expressions for several special cases. With elaboration, it is shown that some results can be expressed in terms of the Meijer G-functions, and one of them is derived through a novel transform. The present results include the SPSC of Rayleigh fading as a special case. Finally, we mention that the present analysis is conducted under the condition that no CSI is available to Alice. If this condition is released, then the *average secrecy capacity* (ASC) is an important metric. The analysis on ASC has been conducted in a companion paper [16] of this author.

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