Performance analysis and optimisation of wireless-powered CRN’S using ambient backscatter communication

by

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Problem statement || Objectives

- **To design an energy efficient ambient backscatter wireless CRN network for an *energy constrained* system that consists of multiple secondary transmitters, spatially distributed, in TDMA and both primary and secondary sensor networks consisting of *heterogeneous channels*, and compare the performance based on Outage, Throughput and SNR.**

- **Mathematical form**

  To empirically derive the mathematical constructs for Outage Probability for the system Model we have constructed for both Rayleigh and Nakagami Channels.

- **Comparative analysis**

  To plot and systematically study the variations of .Outage Probability with reflection coefficient, threshold Signal to Noise Ratio, distance parameters, shape parameters,spread parameters etc,

- **Ablation study**

  To compare the results obtained in both the channel models used with the model used in the base paper to prove superiority of our model, and to finding out the threshold on the number of users

Introduction

Ambient Backscatter Network - **Ambient backscatter** uses existing radio frequency signals, such as radio, television, mobile telephony etc., to transmit data without a battery or power grid connection.

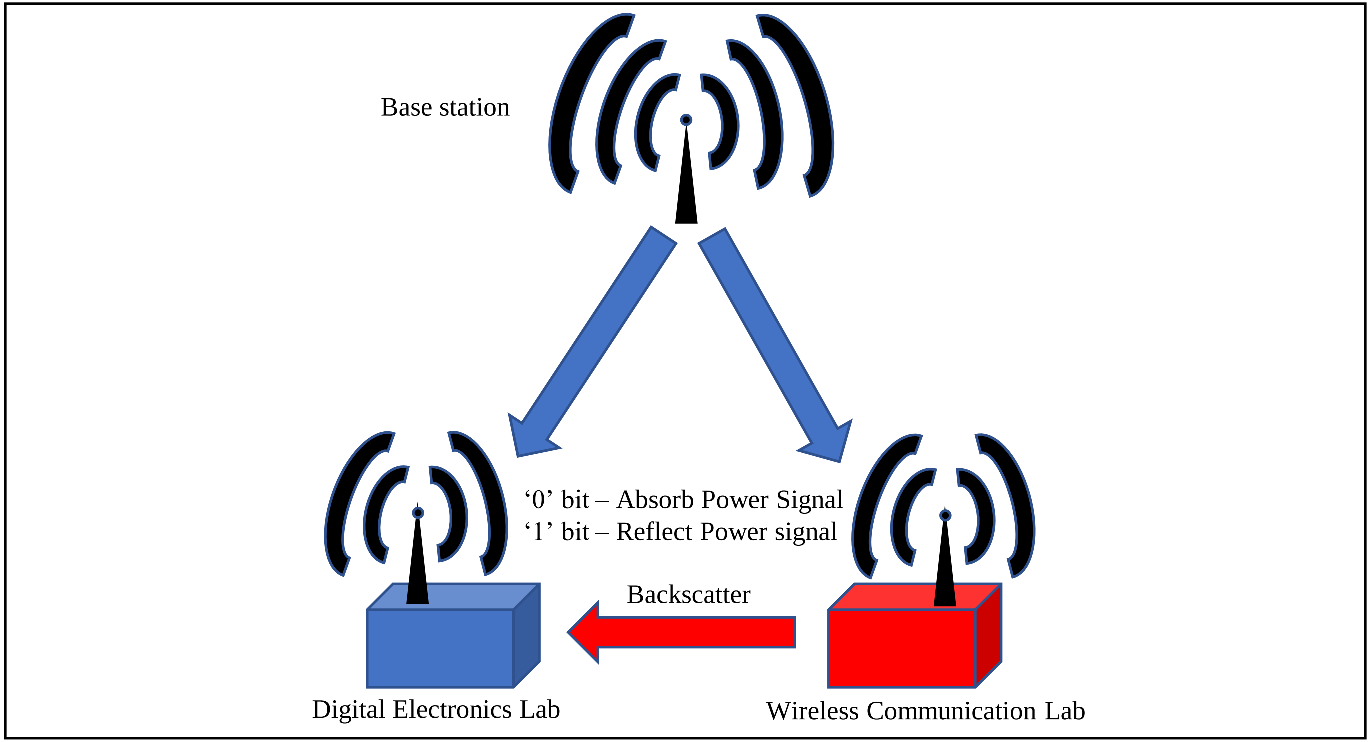
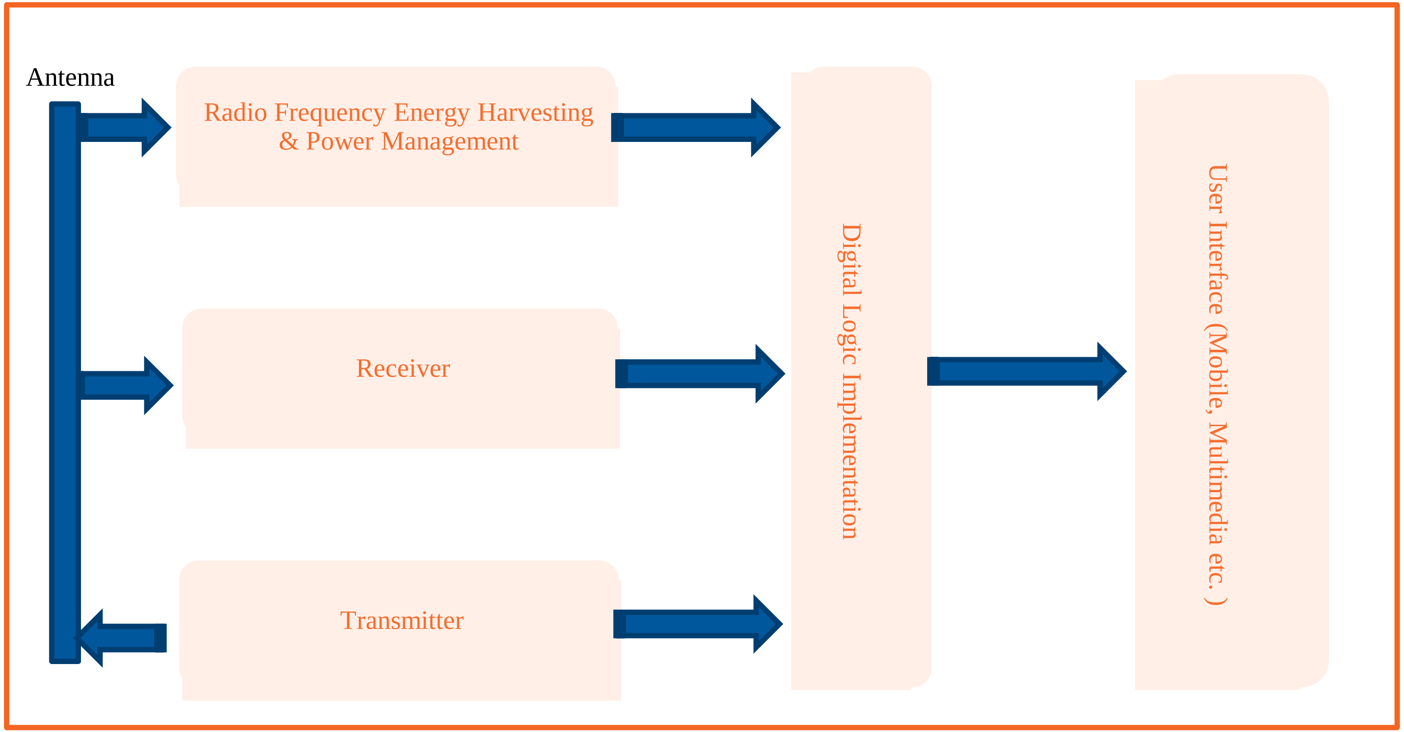


Figure 1



Block Diagram of a backscatter network

Figure 2

Literature Survey on the Outage Probability analysis for backscatter networks

Technology	Paper	Author	Year of publication	Novelty
Designing and development of Backscatter nodes.	Performance characterisation of Relaying using Backscatter Devices	Xiaolun Jia et al.	2018	Usage of Amplify and forward and decode and forward backscatter relaying used.
Multi tag selection combination scheme	Performance Analysis for Tag Selection in Backscatter Communication Systems over Nakagami-m Fading Channels	Yu Zhang et al.	2018	The closed-form analytical outage probabilities for the two correlation circumstances are utilised to perform the study.
A novel ratio detector concept	Signal Ratio detection and Approximate Performance analysis for Ambient Backscatter devices	Shuo Ma et al.	2018	To derive a reasonable approximate expression for the optimal detection threshold using closed form expressions
Underlay Cognitive Network	Performance Analysis of Wireless CRSN's	Daniyal Munir et al.	2019	The outage probability of three symbiotic radio paradigms, namely, commensal, parasitic, and competitive schemes, are studied in a cooperative ambient backscatter system,

Proposed Model

PT - Primary Transmitter

PR - Primary Receiver

STi - i^{th} Secondary Transmitter

SR - Secondary Receiver

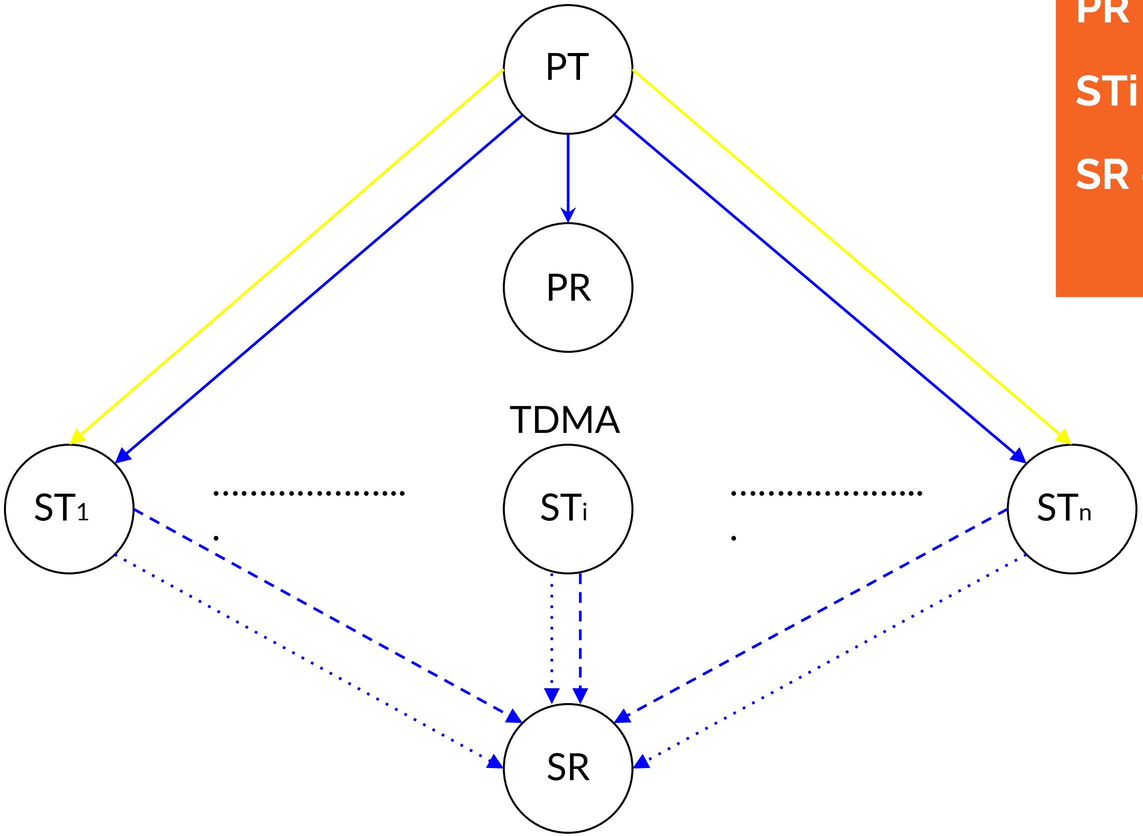


Figure 3

Attributes of proposed model

The proposed novel model involves

-> An ambient backscatter network that has a primary system with one Primary transmitter, one primary receiver, and a secondary backscatter network with multiple secondary transmitters and single secondary receiver.

-> Our model offers a solution to a particular use case of having multiple secondary users in a network, but not enough power (dedicated RF source) to transmit their signals to their respective secondary receivers.

-> In addition, we focus on introducing multiplexing access schemes - TDMA at the access points of the secondary sensor nodes. This is one major contribution that we propose to eliminate the inactivity in the network, thereby reducing the idle time and improving the overall network efficiency.

-> Our model optimizes the power received at the secondary sensor network ie., the secondary transmitting nodes use only the basic amount of power needed to transfer the message bits to the corresponding secondary receivers, and the excess power is stored and harvested for other applications like powering LED's, converting into other forms of energy, stored to meet other power demands,

-> Design of an efficient backscatter network with more efficiency, less waiting time, and inbuilt harvesting mechanisms with the help of cognitive and multiplexing schemes.

Mathematical derivations for our proposed model

We know, $$Sn = \alpha(\sqrt{Ps}hx + n1)$$

Secondary TVans

$$\alpha\left(\sqrt{Ps}(hg)x + n1g\right)$$

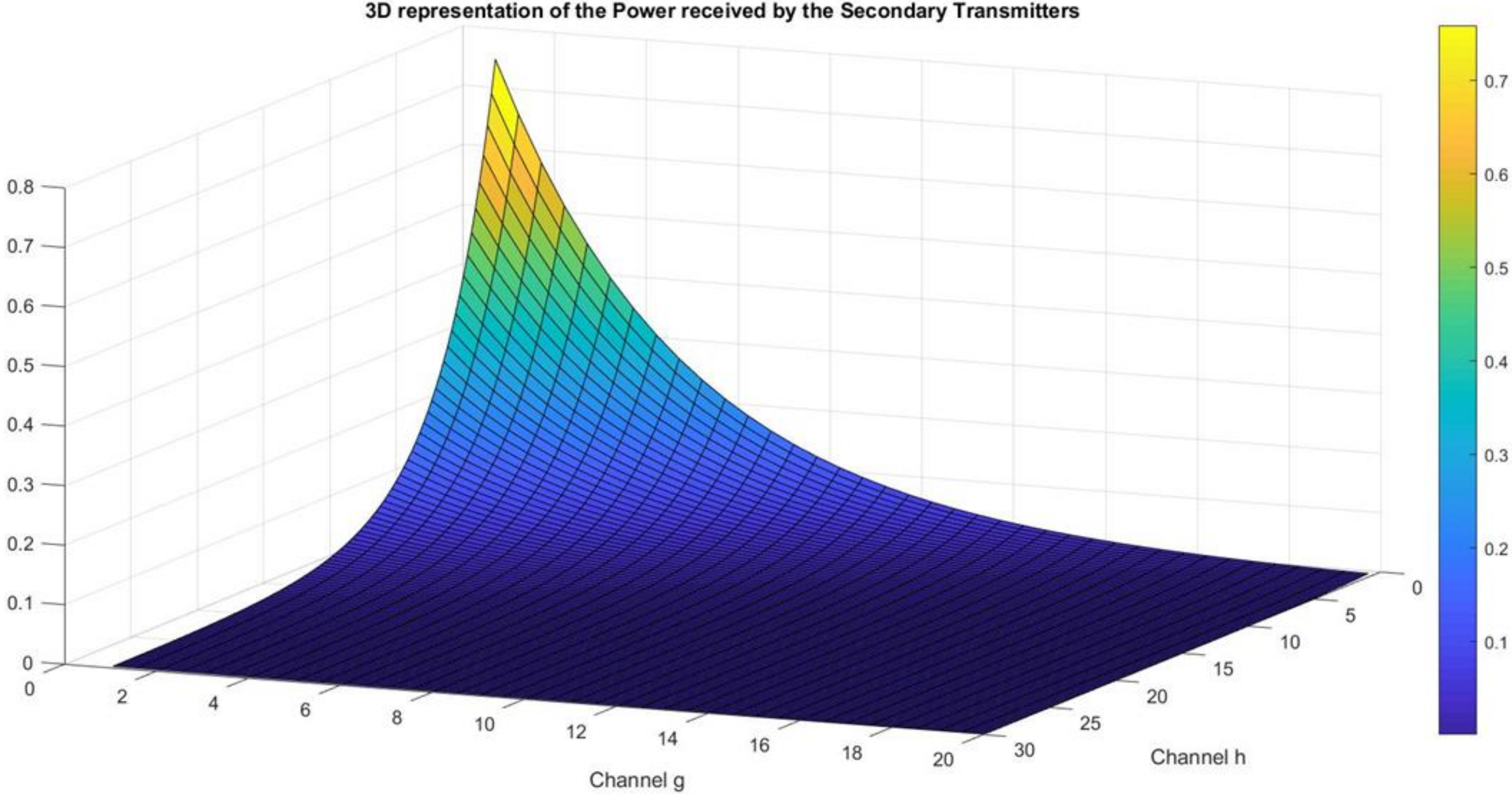
$$Srcvr = \alpha\sqrt{Ps}(hg)x + \alpha n1g + n2 \qquad (1)$$

Secondary Receiver

We attempt to minimize this parameter

Key:
h, g are channel PDF's; n1,n2 = AWGN
α: Reflection Coefficient; Ps = Power Src

Figure 4



Simulation obtained by plotting the variation of the output Signal (in equation (1) received at the secondary transmitter with respect to the two channels – h and g. This has been done on MATLAB.

$$Sr = \alpha\sqrt{Ps}xhg + n2 \longrightarrow \quad (2)$$

$$SNR = \frac{\alpha Ps|h|^2|g|^2}{{\sigma_N}^2} \quad \text{(By definition)}$$

$$P_{out} = P(C < R)$$

where R is assumed as the channel capacity threshold

$$\{\, C = \quad \log_2(1 + SNR) < R \,\}$$

$$= \log_2(1 + SNR) < R$$

$$= 1 + SNR < 2^R$$

$$= SNR < 2^R - 1$$

$$= \frac{\alpha^2 P_S |h|^2 |g|^2}{\sigma_N^2} < 2^R - 1$$

$$= |g|^2 < \frac{(2^R - 1)\sigma_N^2}{\alpha P_s |h|^2}$$

$$P_{out} = \int_0^\infty |g|^2 < \frac{(2^R - 1)\sigma_N^2}{\alpha P_s |h|^2} f_g(n) dx$$

= limits of g are from $0 \to \dfrac{(2^R - 1)\sigma_N^2}{\alpha P_s |h|^2}$

Key:
R = Threshold Channel Capacity; **Ω**g = Distance parameter of channel g; **Ω**h= Distance parameter of channel h

$$fg(n) = \frac{1}{\Omega g} exp(\frac{-x}{\Omega g})$$ (Rayleigh distribution) → **(3)**

$$P_{out} = \int_0^\infty \int_0^{\frac{(2^R-1)\sigma_N^2}{\alpha P_S |h|^2}} \frac{1}{\Omega g} exp(\frac{-x}{\Omega g}) dx$$

$$\frac{-x}{\Omega g} = t$$

Substituting (3)

$$-dx = \Omega g dt$$

$$= \ - exp(\frac{-x}{\Omega g})$$

$$= \int_{0}^{\infty} -exp(\frac{-x}{\Omega g})\Big|_{0}^{\frac{(2^R-1)\sigma_N^2}{\alpha P_s |h|^2}} \qquad (4)$$

Substitutions in equation 4:

$$\gamma_{TH} = 2^R - 1$$

$$\frac{P_s}{\sigma^2} = \gamma$$

$$|h|^2 = y$$

$$= \int_{0}^{\infty} (1 - exp(\frac{-\gamma_{TH}}{\alpha \gamma y})$$

$$= \int_{0}^{\infty} f_y(y) dy$$

$$f_y(y) = \frac{1}{\Omega y} exp(\frac{-y}{\Omega y})$$

(Rayleigh Distribution)

$$=\int_0^\infty ((1-exp(\frac{-\gamma_{TH}}{\alpha\gamma y}))\frac{1}{\Omega y}exp(\frac{-y}{\Omega y})dy$$

$$=\int_0^\infty \frac{1}{\Omega y}exp(\frac{-y}{\Omega y})-\frac{1}{\Omega y}exp(\frac{-y}{\Omega y})exp(\frac{-\gamma_{TH}}{\alpha\gamma y})dy$$

$$=\int_0^\infty \frac{1}{\Omega y}exp(\frac{-y}{\Omega y})dy-\int_0^\infty \frac{1}{\Omega y}exp(\frac{-y}{\Omega y})exp(\frac{-\gamma_{TH}}{\alpha\gamma y})dy$$

$$-exp(\frac{-y}{\Omega y})\Big|_0^\infty$$

$$1-exp(-\infty)-\int_0^\infty \frac{1}{\Omega y}exp(\frac{-y}{\Omega y})exp(\frac{-\gamma_{TH}}{\alpha\gamma y})dy$$

$$=1-\sqrt{x}k_1\sqrt{x} \qquad (Integration Formula)$$

(Where k1 ∈ Bessel F'n) Referring equation 3.81 in the book mentioned in References

$$P_{out}=1-\sqrt{\frac{\gamma_{TH}}{\alpha\Omega_g\Omega_h\gamma}}k_1(\sqrt{\frac{\gamma_{TH}}{\alpha\Omega_g\Omega_h\gamma}}) \qquad (5)$$

Simulation parameters - Rayleigh

Matlab Code

```
clc
close all;
d=0.5; alpha=2;
r=1;
%%% Threshold for SNR detection
gamma_th=2^r-1;
 %%% distance parameter
sigma_g=d^-alpha;
sigma_r=(1-d)^-alpha;
%%%Reflection co-efficient
beta=0.5;
snr_dB=-20:40;
snr_lin=10.^(snr_dB./10);
% Number of secondary transmitters
M=3;
```

Values of parameters taken to obtain **simulation**

Distance d = 0.5
α = 2;
r = 1;
X = 1;

Distance parameters for rayleigh model:
Ω_g = 0.5;
Ω_r = 0.5;

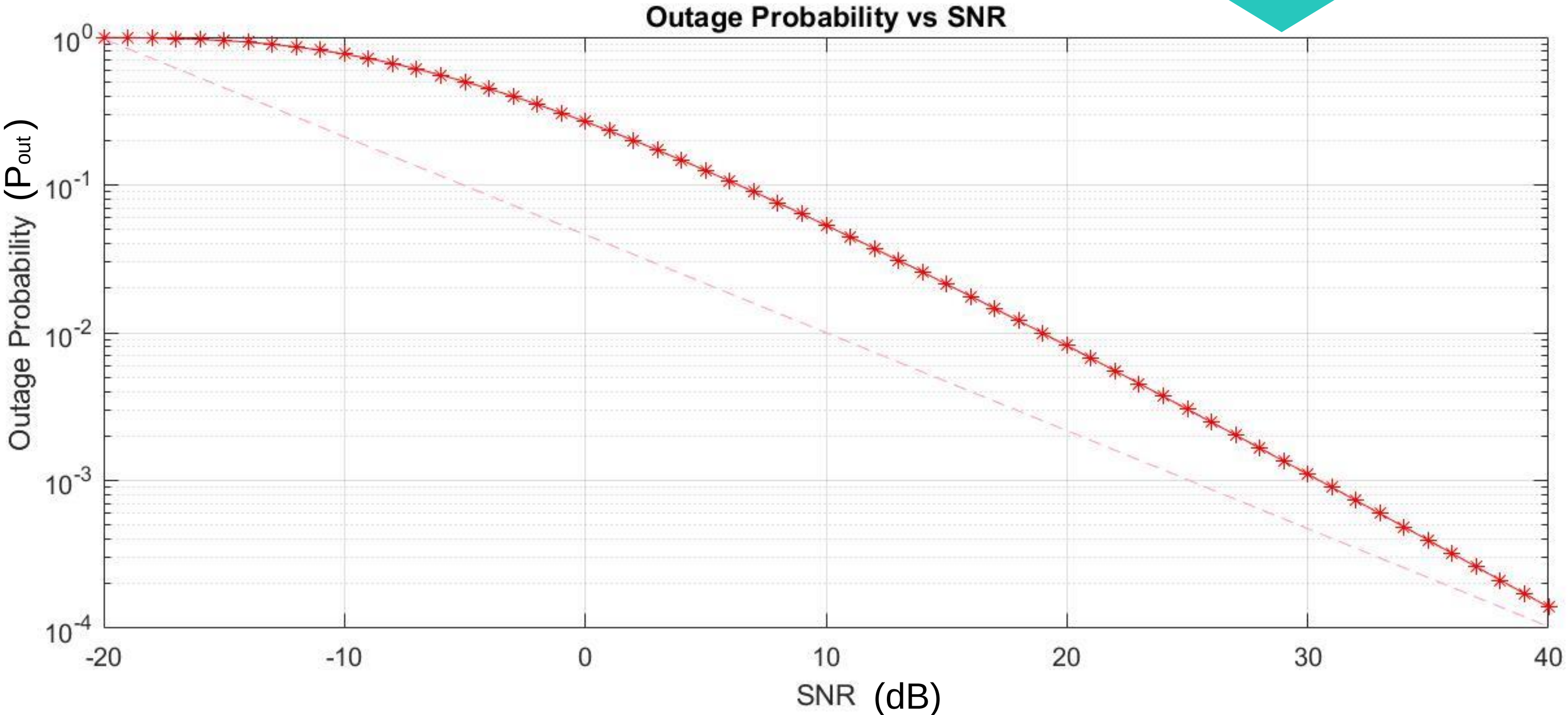
β = 0.5;

M = 3; Number of secondary transmitters

Simulations

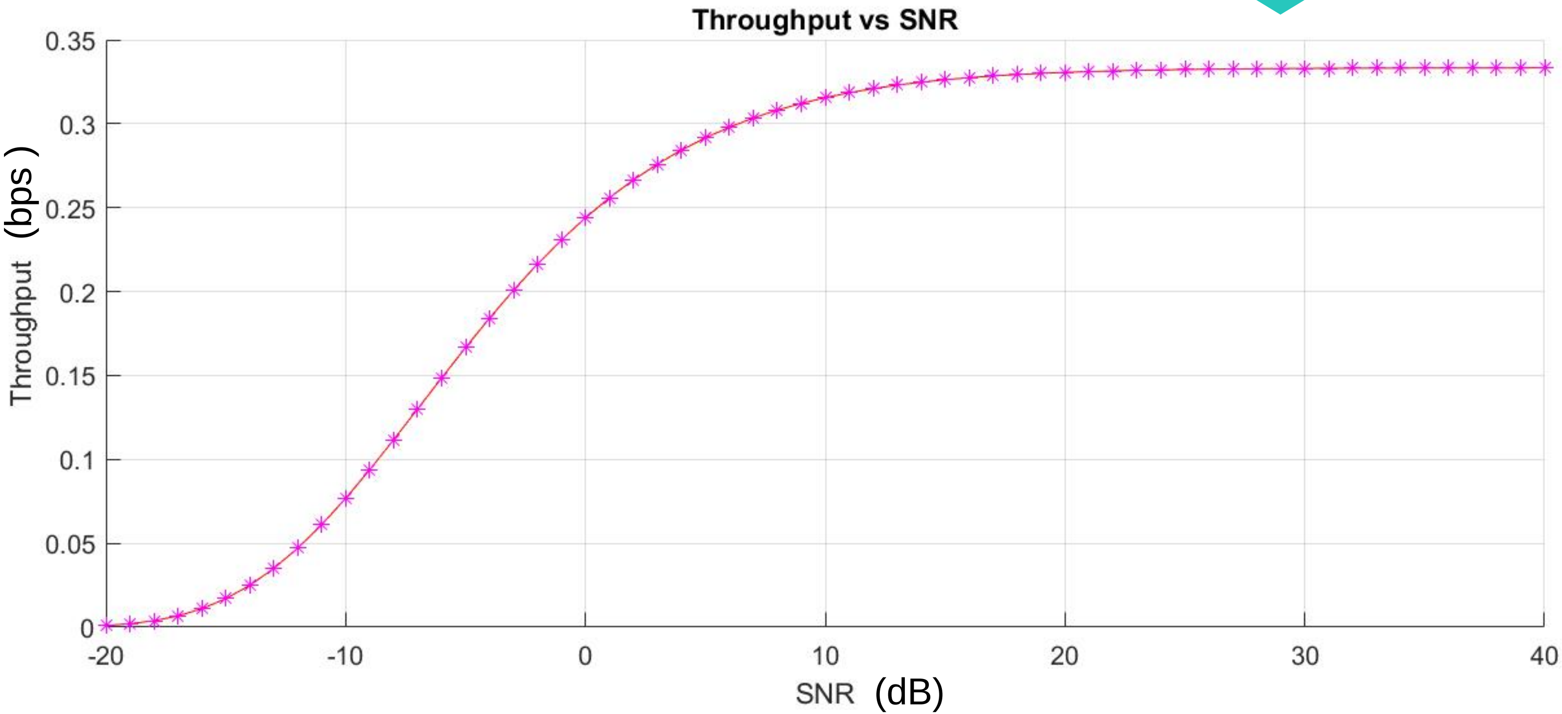
Variation of Outage Probability with SNR

Figure 5



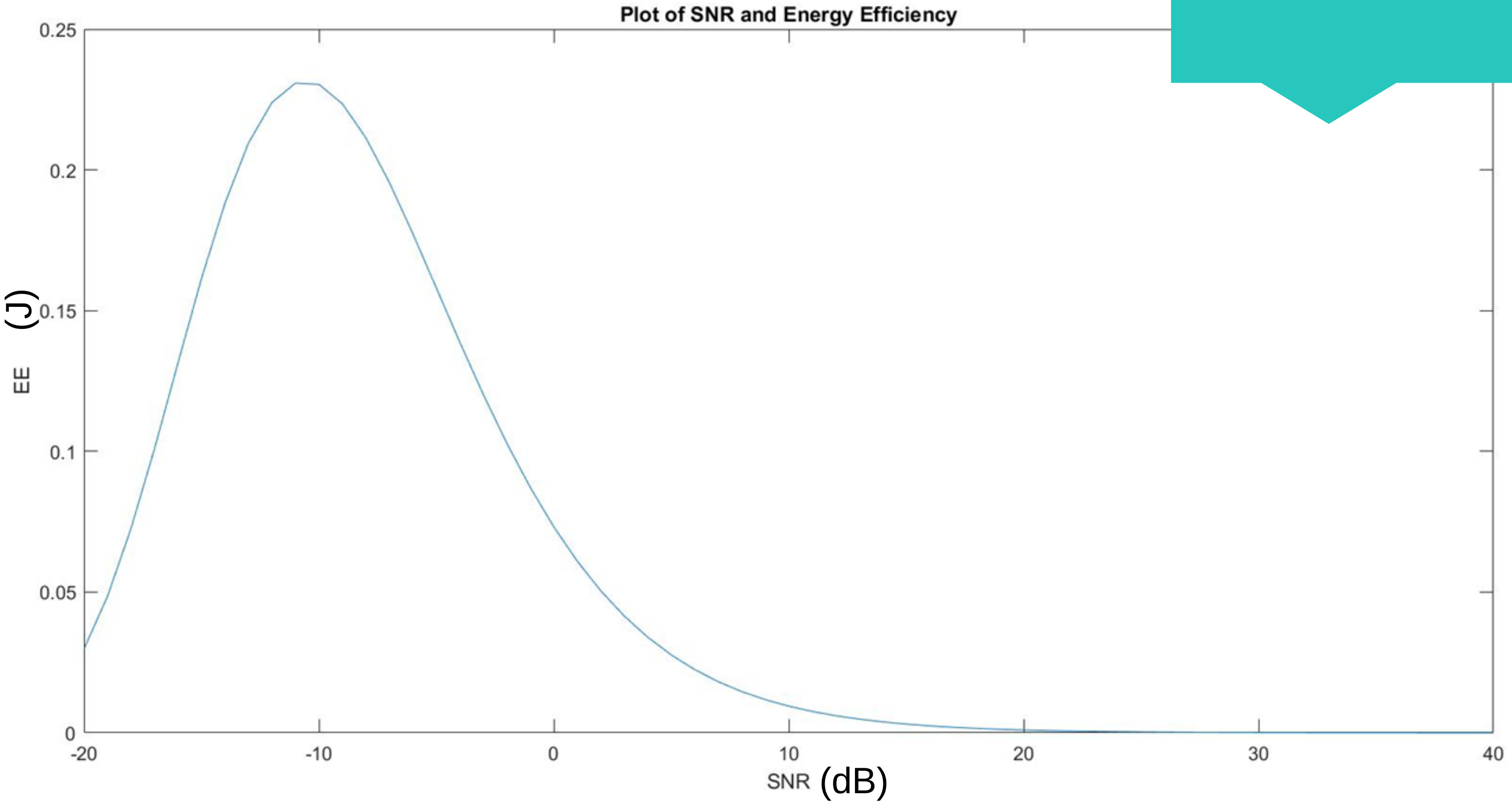
Variation of Throughput with SNR

Figure 6



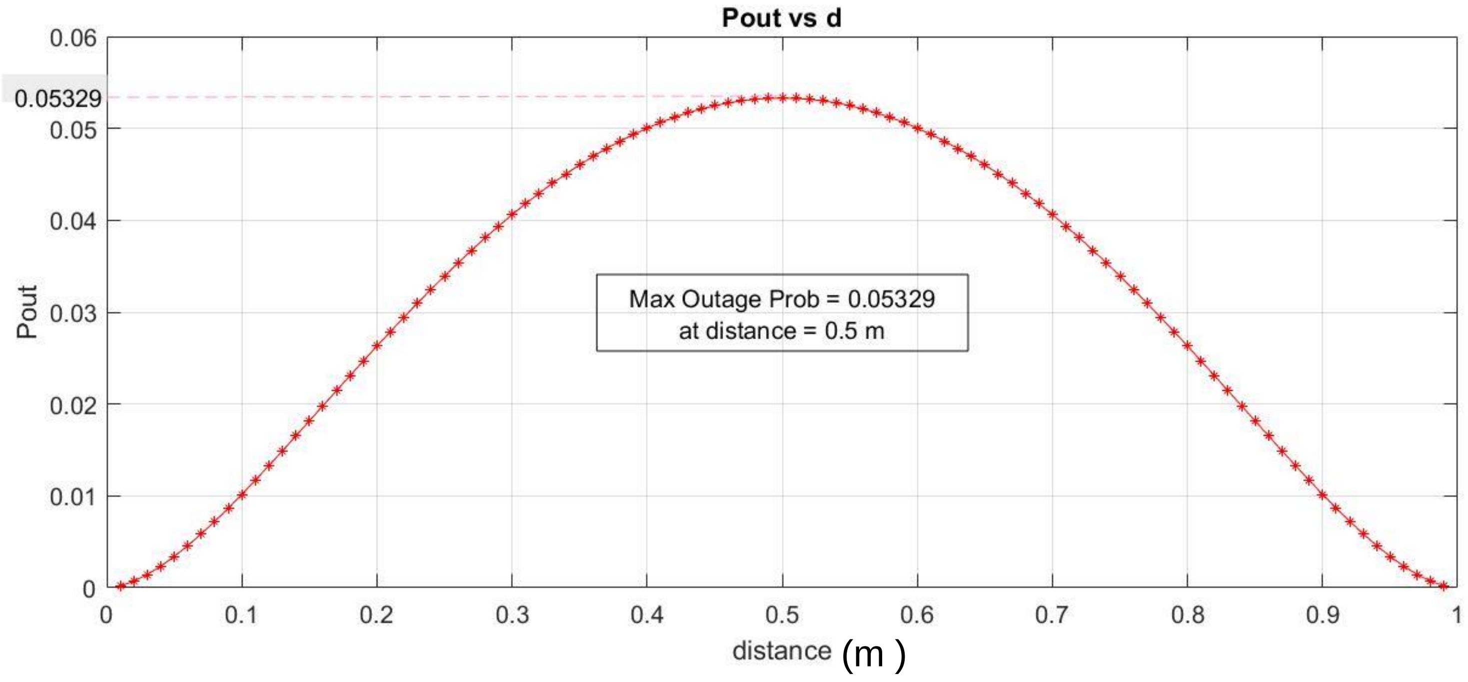
Variation of Energy Efficiency with SNR

Figure 7



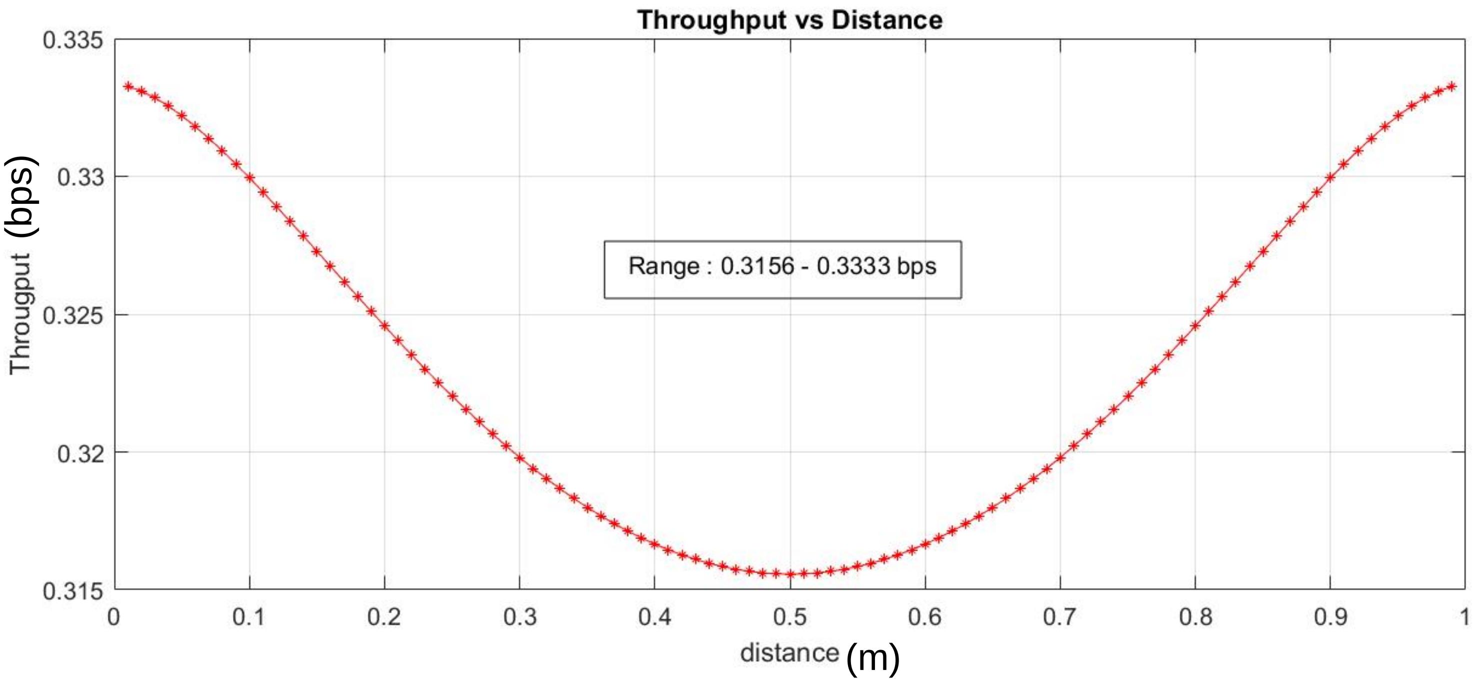
Variation of Outage Probability with distance

Figure 8



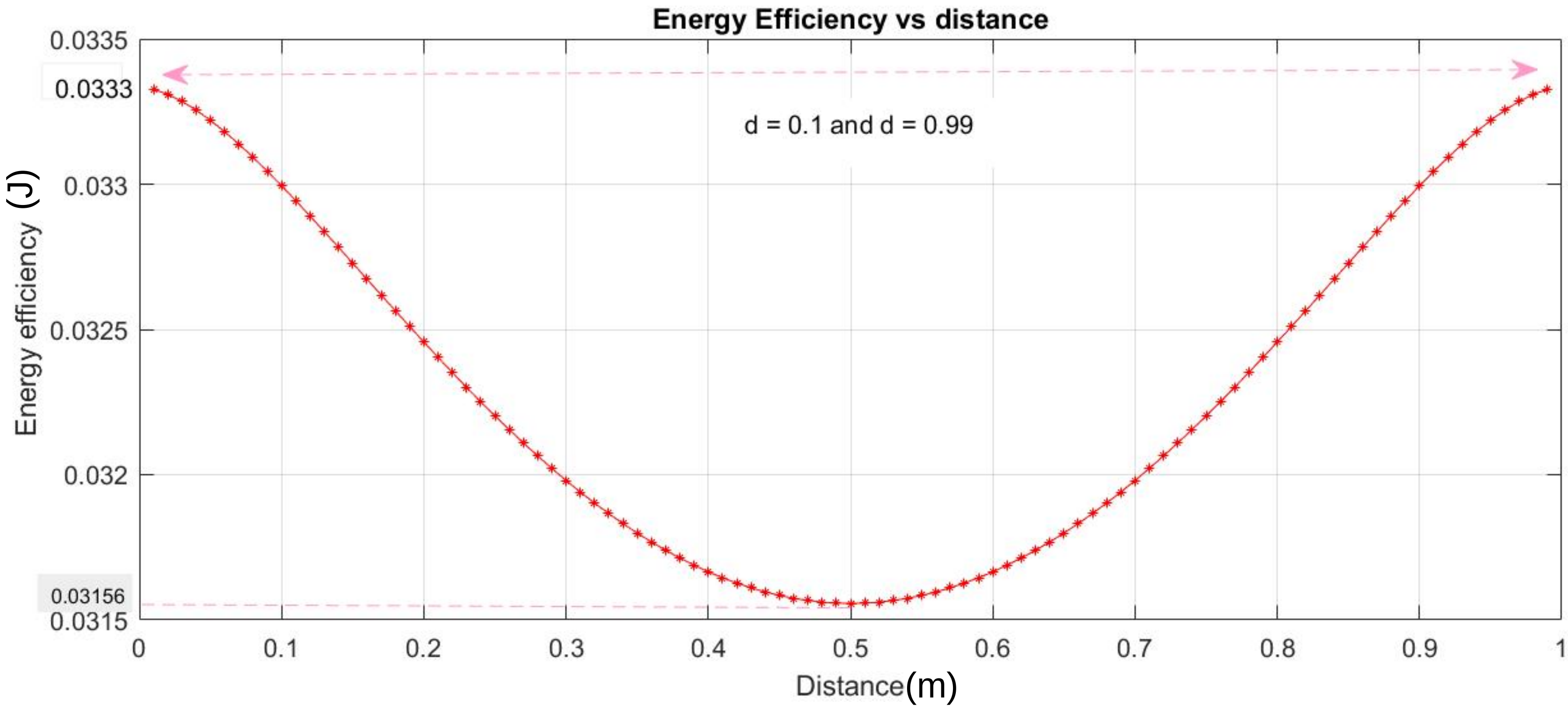
Variation of Throughput with distance

Figure 9



Variation of Energy Efficiency with SNR

Figure 10



Mathematical derivations for Nakagami model

$$P_\gamma(\gamma_{SR} > \gamma_{th}) = P_\gamma(\phi|h_{dn}|^2|h_{dn}|^2 > \gamma_{th})$$

$$= P_\gamma(x > \frac{\gamma_{th}}{\phi y}) \longrightarrow \quad \text{(1)}$$

$$\boxed{\frac{x - h_{dn}}{y - h_{dn}}}$$

First integrating wrt ‘x’ keeping ‘y’ constant

$$= \int_{\frac{\gamma_{th}}{\phi y}}^{\infty} (\frac{m_d}{\Omega_d})^{m_d} \frac{x^{m_d-1}}{\gamma(m_d)} exp(\frac{-m_d x}{\Omega_d}) dx$$

$$= (\frac{m_d}{\Omega_d})^{m_d} . \frac{1}{\gamma(m_d)} \int_{\frac{\gamma_{th}}{\phi y}}^{\infty} x^{m_d-1} exp(\frac{-m_d x}{\Omega_d}) dx$$

Using formula from Tables of Integrals equation 3.381

$$i.e = \int_u^\infty x^{v-1} e^{-ux} dx = u^{-v} \gamma(v, \mu u)$$

$$We\ get\ P_r(\gamma_{SR} > \gamma_{th})\ after\ putting\ z = \frac{\gamma_{th}}{\phi y}, v = m_d\ and\ \mu = \frac{m_d}{\Omega_d}$$

$$= (\frac{m_d}{\Omega_d})^{m_d} . \frac{1}{\gamma(m_d)} . (\frac{m_d}{\Omega_d})^{-m_d} . \gamma(m_d, \frac{m_d \gamma_{th}}{\Omega_d \phi y})$$

$$= \frac{1}{\gamma(m_d)} . \gamma(m_d, \frac{m_d \gamma_{th}}{\Omega_d \phi y}) \longrightarrow \quad (2)$$

Now integrating wrt ‘y’

$$= \int_0^\infty \frac{1}{\gamma(m_d)} . \gamma(m_d, \frac{m_d \gamma_{th}}{\Omega_d \phi y})(\frac{m_u}{\Omega_u})^{m_u} \frac{y^{m_u - 1}}{\gamma(m_u)} exp(\frac{-m_u y}{\Omega_u}) dy$$

$$= \frac{1}{\gamma(m_d)\gamma(m_u)} (\frac{m_u}{\Omega_u})^{m_u} \int_0^\infty y^{m_u - 1} \gamma(m_d, \frac{m_d \gamma_{th}}{\Omega_d \phi y}) exp(\frac{-m_u y}{\Omega_u}) dy$$

Converting incomplete gamma function in simple form using

$$\gamma(s,x) = (s-1)!e^{-x}\sum_{k}^{s}\frac{x^k}{k!};$$ s is +ve integer {Substituting the approximation formula}

$$We\ can\ write\ P_\gamma(\gamma_{SR} > \gamma_{th})\ as$$

$$= \frac{1}{\gamma(m_d)\gamma(m_u)}(\frac{m_u}{\Omega_u})^{m_u}\int_0^\infty y^{m_u-1}(m_d-1)!e^{\frac{-m_d\gamma_{th}}{\phi\Omega_d y}}\sum_{k=0}^{m_d-1}(\frac{-m_d\gamma_{th}}{\phi\Omega_d y})^k\frac{1}{k!}exp(\frac{-m_u y}{\Omega_u})dy$$

$$= \frac{(m_d-1)!}{\gamma(m_d)\gamma(m_u)}(\frac{m_u}{\Omega_u})^{m_u}\sum_{k=0}^{m_d-1}\frac{1}{k!}(\frac{m_d\gamma_{th}}{\phi\Omega_d})^k\int_0^\infty y^{-k}.y^{m_u-1}exp(\frac{-m_d\gamma_{th}}{\phi\Omega_d}-\frac{m_u y}{\Omega_u})dy$$

(3)

Using formula from Tables of Integrals equation 3.478

$$i.e\int_0^\infty x^{v-1}exp(-\beta x^p-\gamma x^{-p})dx = \frac{2}{P}(\frac{\gamma}{\beta})^{\frac{v}{2p}}K_{\frac{V}{P}}(2\sqrt{\beta\gamma})$$

$$there\ \beta = \frac{m_u}{\Omega_u}, \gamma = \frac{m_d\gamma_{th}}{\phi\Omega_d}, v = m_u - k, p = 1$$

$$= \frac{(m_d-1)!}{\gamma(m_d)\gamma(m_u)}(\frac{m_u}{\Omega_u})^{m_u}\sum_{k=0}^{m_d-1}(\frac{m_d\gamma_{th}}{\phi\Omega_d})^k.\frac{1}{k!}.2(\frac{m_d\gamma_{th}\Omega_u}{\phi\Omega_d m_u})^{\frac{m_u-k}{2}}K_{m_u-k}(2\sqrt{\frac{m_u m_d\gamma_{th}}{\phi\Omega_d\Omega_u}})$$

$$= \frac{(m_d-1)!}{\gamma(m_d)\gamma(m_u)}(\frac{m_u}{\Omega_u})^{\frac{m_u}{2}}(\frac{m_d\gamma_{th}}{\phi\Omega_d})^{\frac{m_u}{2}}\sum_{k=0}^{m_d-1}(\frac{m_d\gamma_{th}}{\phi\Omega_d})^k.\frac{2}{k!}(\frac{m_d\gamma_{th}\Omega_u}{\phi\Omega_d m_u})^{\frac{-k}{2}}K_{m_u-k}(2\sqrt{\frac{m_u m_d\gamma_{th}}{\phi\Omega_d\Omega_u}})$$

$$= \frac{(m_d-1)!}{\gamma(m_d)\gamma(m_u)}(\frac{m_u m_d\gamma_{th}}{\phi\Omega_d\Omega_u})^{\frac{m_u}{2}}\sum_{k=0}^{m_d-1}\frac{2}{k!}(\frac{m_d\gamma_{th}}{\phi\Omega_d})^{\frac{k}{2}}(\frac{\Omega_u}{m_u})^{\frac{-k}{2}}K_{m_u-k}(2\sqrt{\frac{m_u m_d\gamma_{th}}{\phi\Omega_d\Omega_u}})$$

$$Let\ \sqrt{\frac{m_u m_d\gamma_{th}}{\phi\Omega_d\Omega_u}} = \sigma$$

Final Outage Expression

$$Pout = 1 - P_{\gamma}(\gamma_{SR} > \gamma_{th})$$

$$= \frac{2(m_d - 1)!}{\gamma(m_d)\gamma(m_u)} . \sigma^{m_u} \sum_{k=0}^{m_d-1} \frac{1}{k!} \sigma^k K_{m_u - k}(2\sigma) \qquad (5)$$

Equation 5 gives us the final outage expression for a Nakagami model with the given shape and spread parameters

Simulation parameters - Nakagami

Matlab Code

```
clc
close all;
mf = 2; sigma_f = 1; %phase3 parameters
r=1;
mu=2;md=4; %shape parameters
gamma_th=2^r-1; %%% Threshold for SNR
sigma_u=1; sigma_d=1; %spread parameters
alpha=0.5;  %%%Reflection co-efficient
snr_dB=-20:40;
snr_lin=10.^(snr_dB./10);
% formula for incomplete gamma function
%gamma(s,x)= (s-1)! * e(^-x)*
sigma from (k=0 to s-1) of x^k/k!

sig = sqrt((mu.*md.*gamma_th)./
(sigma_u.*sigma_d.*alpha.*snr_lin));
```

Values of parameters taken to obtain **simulation**

α = 0.5;
r = 1;
X = 1;

Spread parameters for Nakagami model:
Ω_u = 1;
Ω_d = 1;

Shape Parameters for Nakagami model:
mu = 2;
md = 4;

M = 3; Number of secondary transmitters

Simulations (Nakagami)

Variation of Outage Probability with SNR

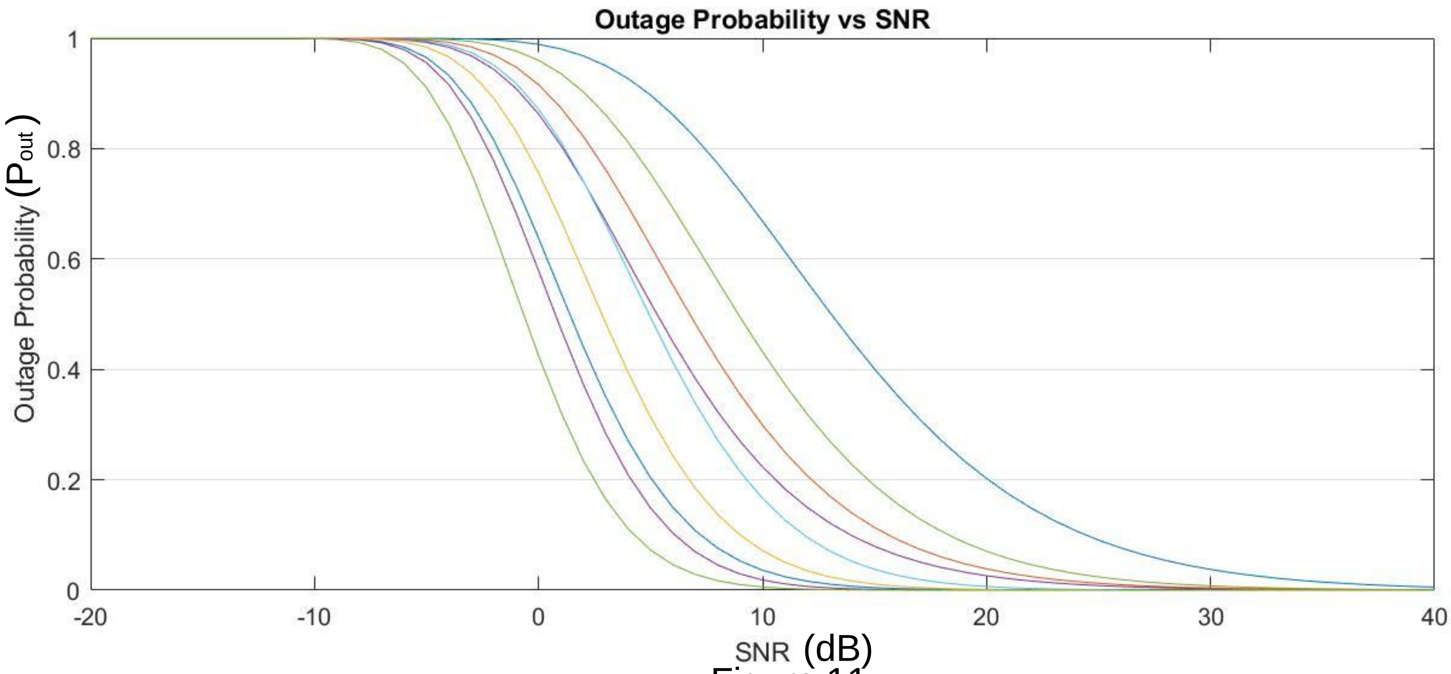
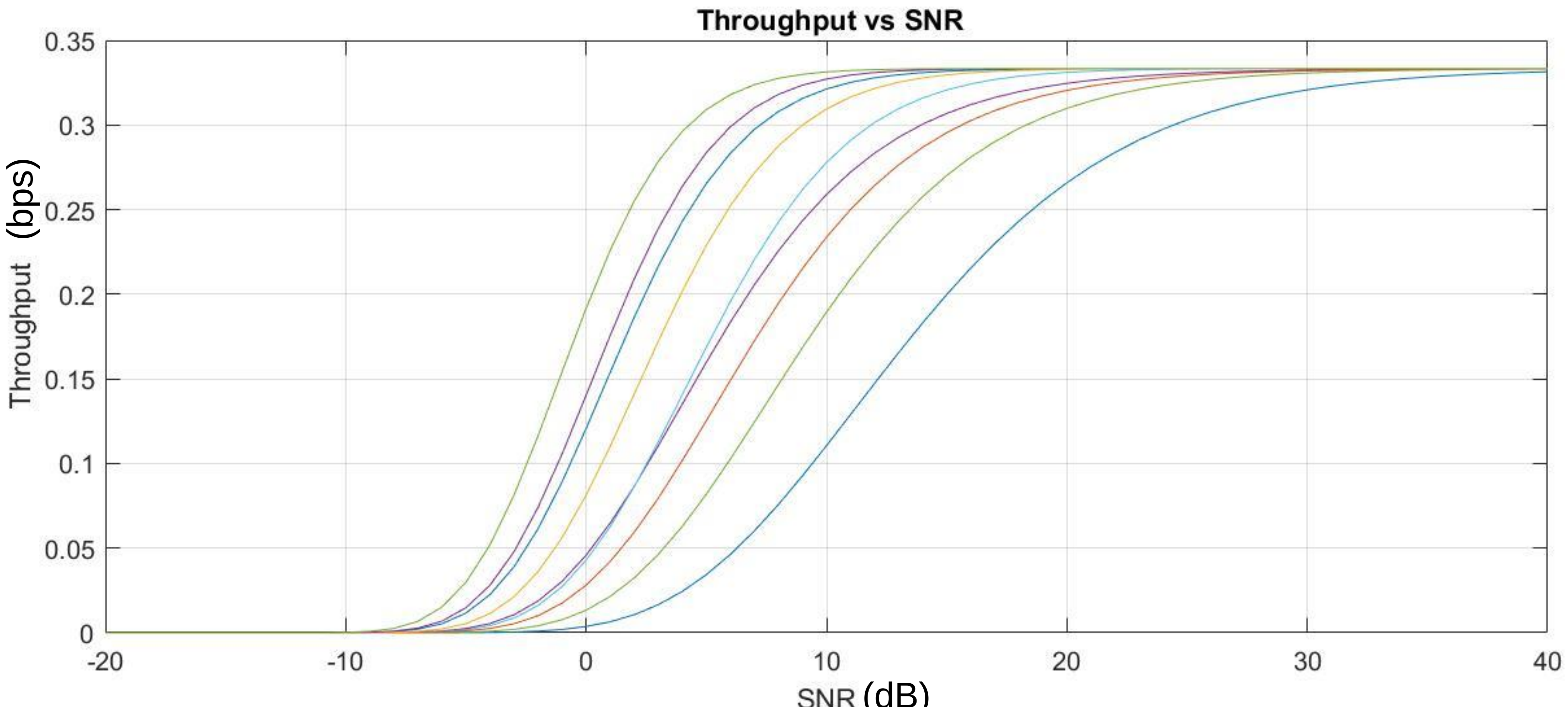


Figure 11

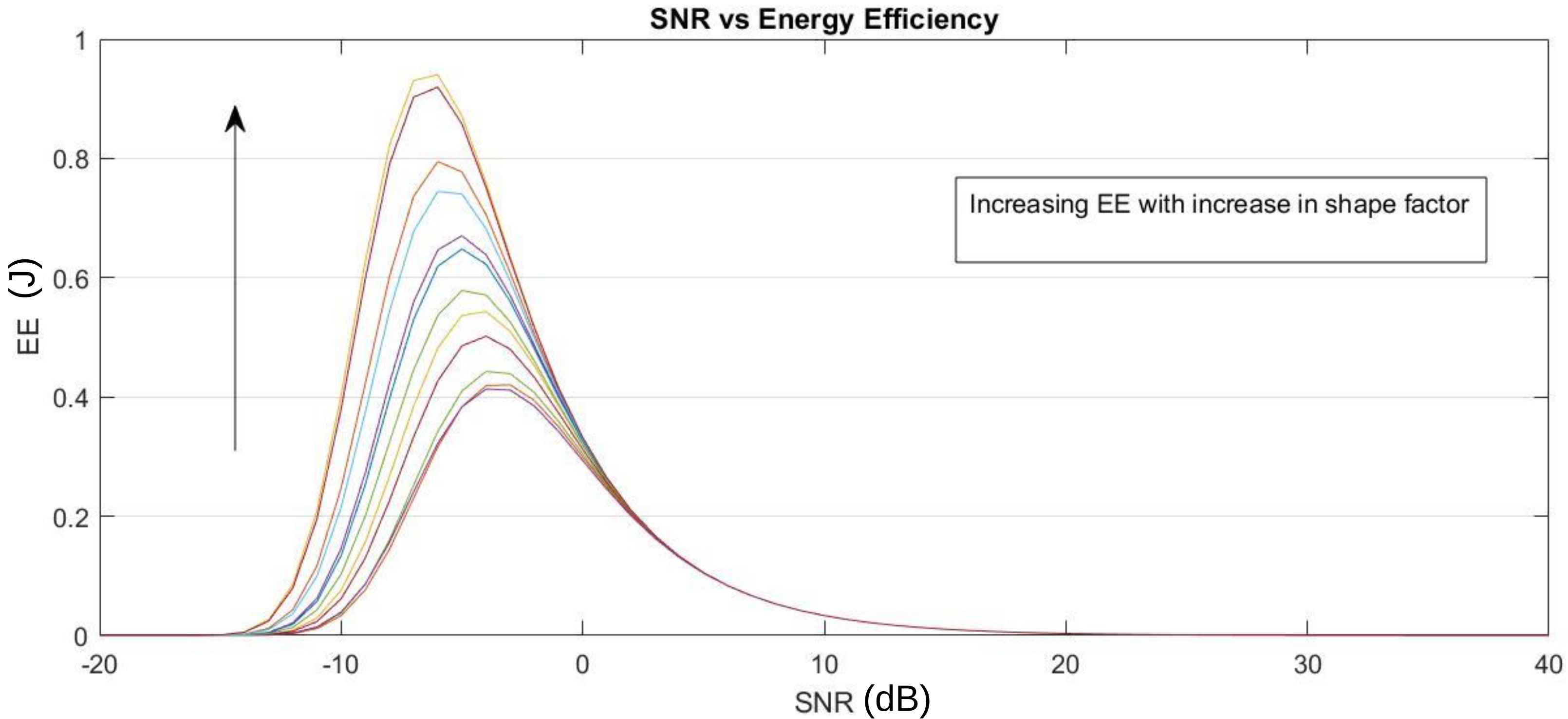
Variation of Outage Probability with SNR

Figure 12



Variation of Outage Probability with SNR

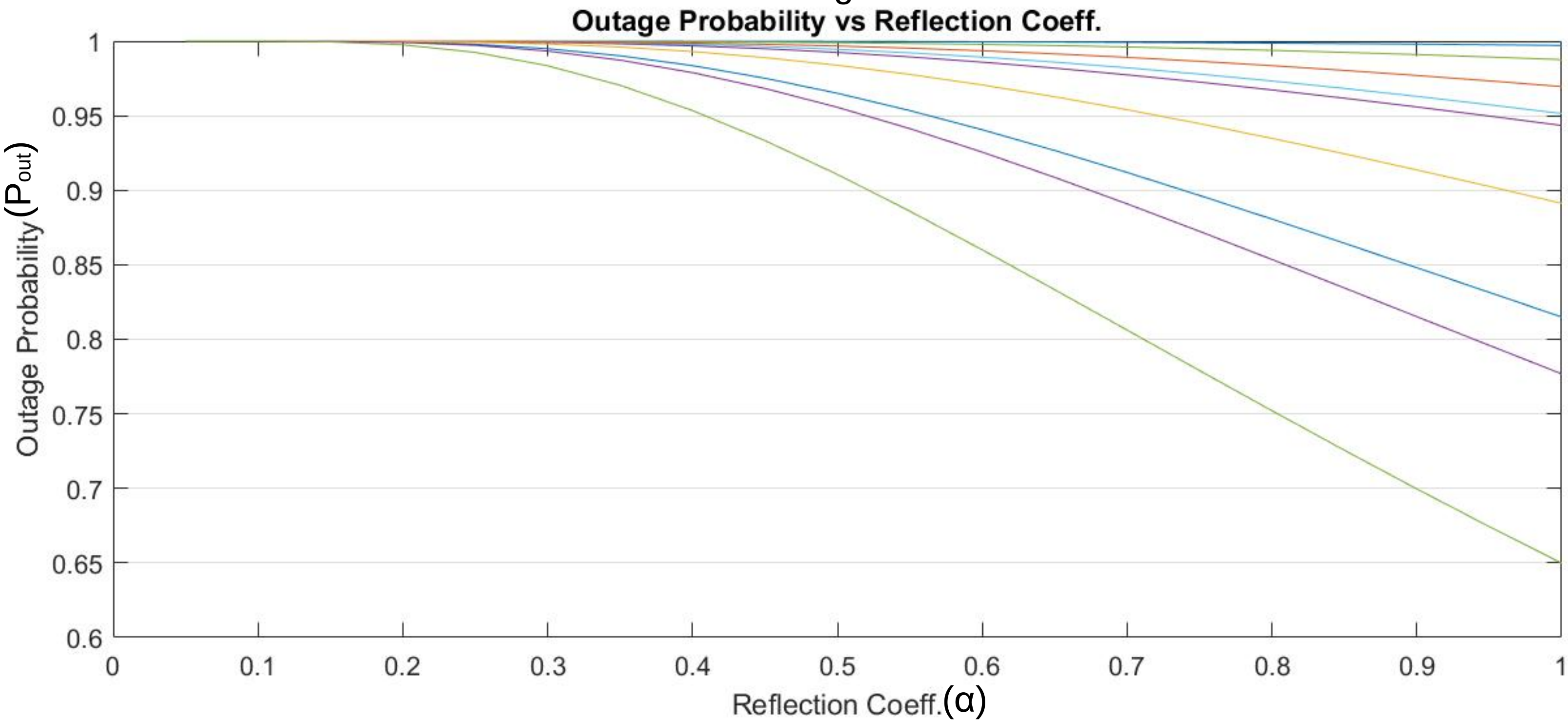
Figure 13



Variations with Ref Coeff(Nakagami)

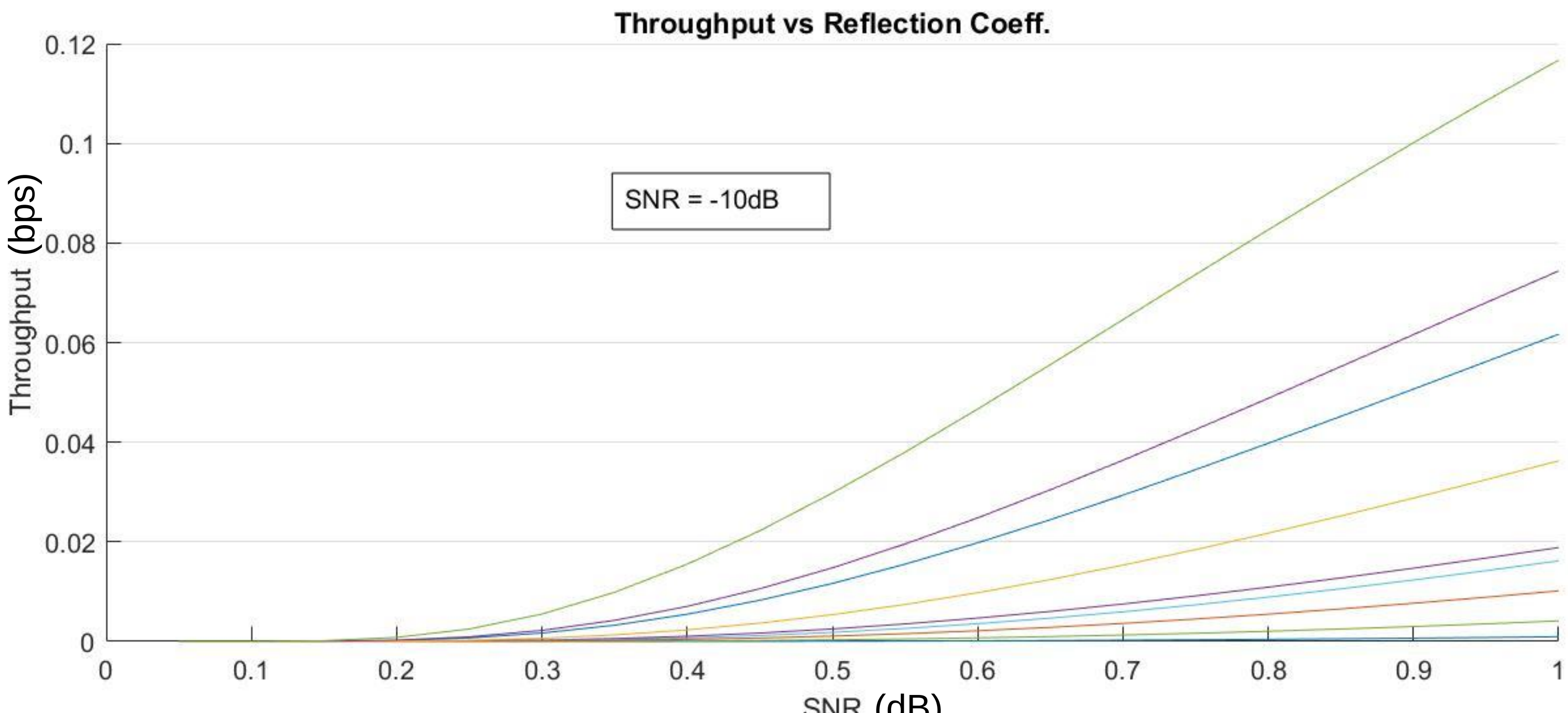
Variation of Outage Probability with Reflection coeff.

Figure 14



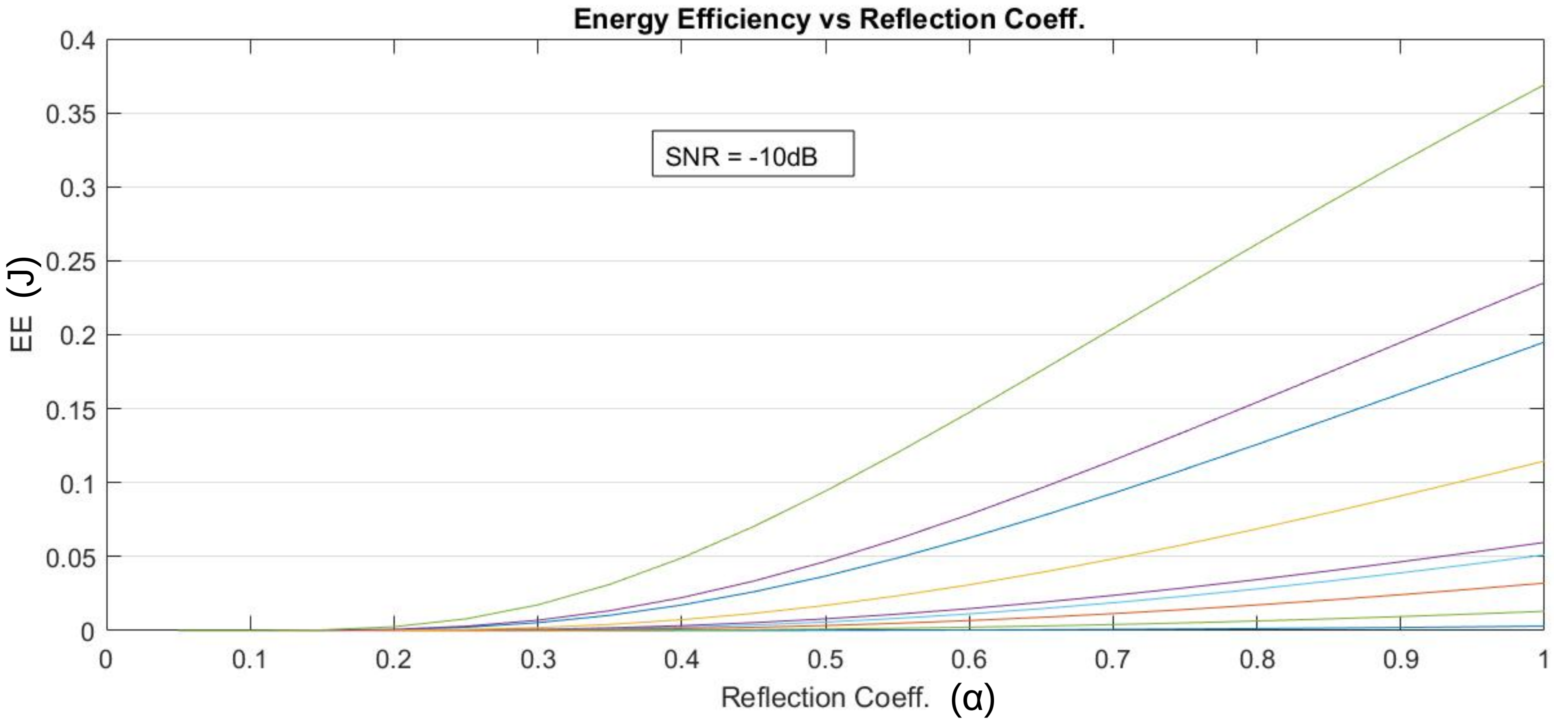
Variation Throughput with Reflection coeff.

Figure 15



Variation of Energy Efficiency with Reflection coeff.

Figure 16



Variations with number of secondary transmitters

Variation of Outage Prob. with M varying SNR

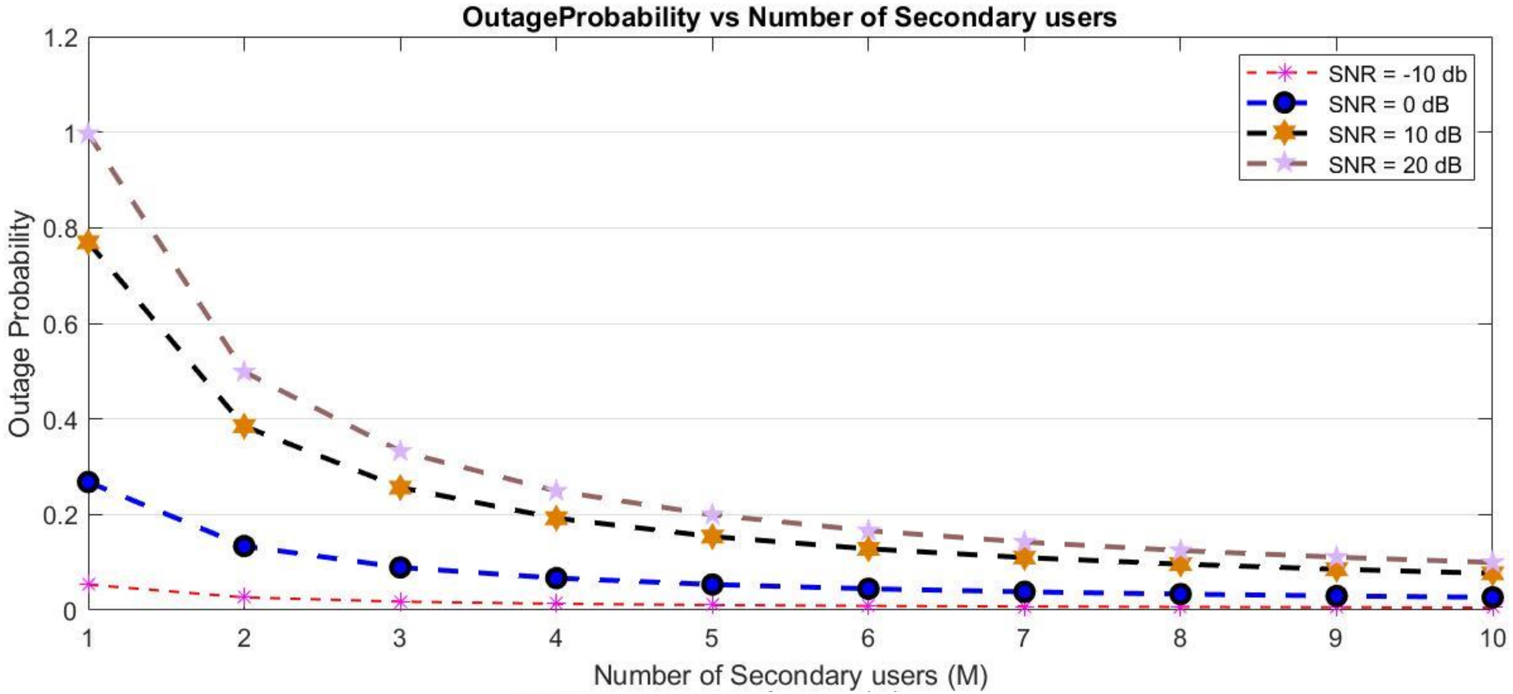


Figure 17

Variation of Outage Prob. with M varying Beta

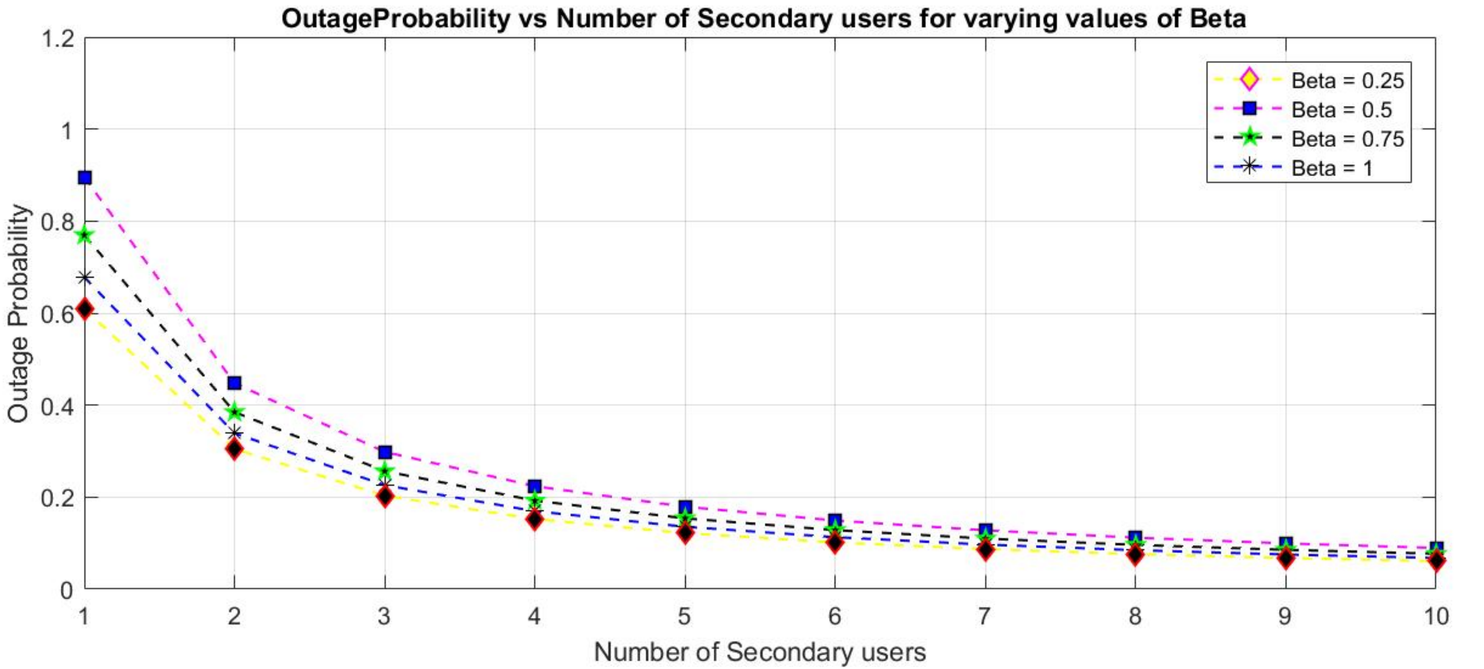


Figure 18

Variation of Outage Prob. with M varying distance

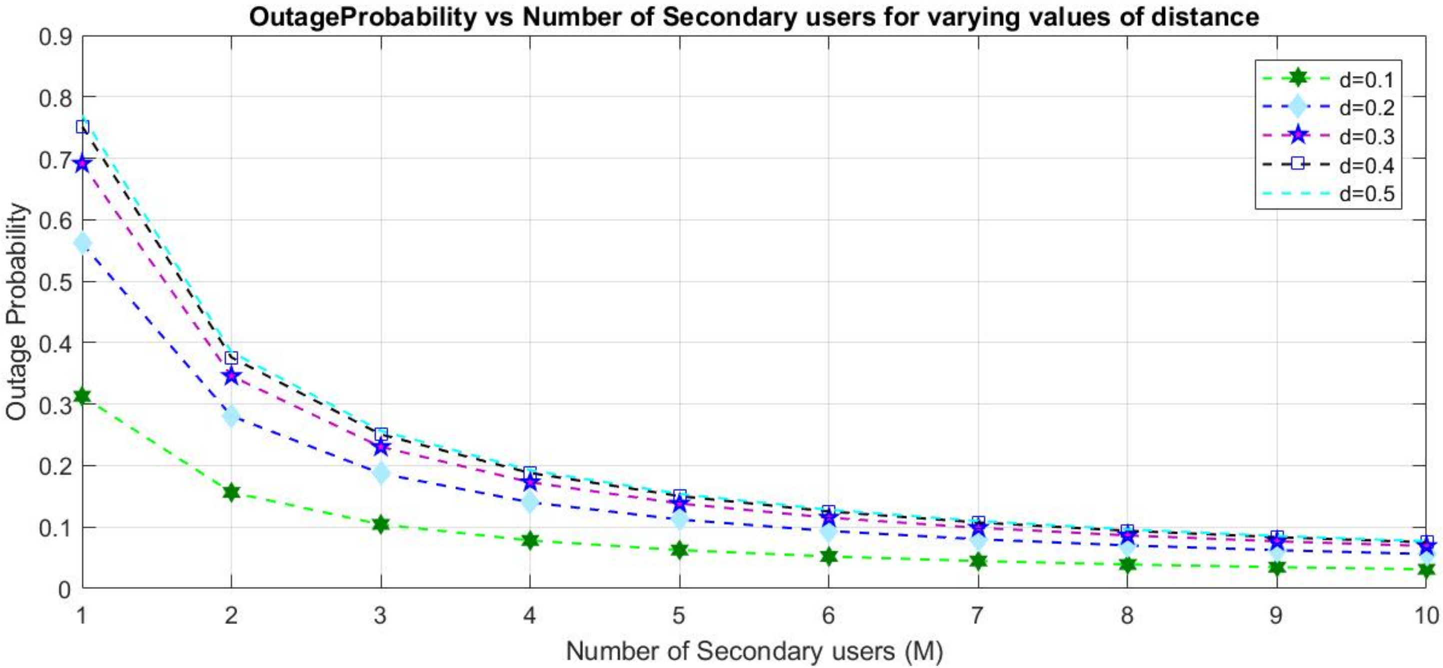
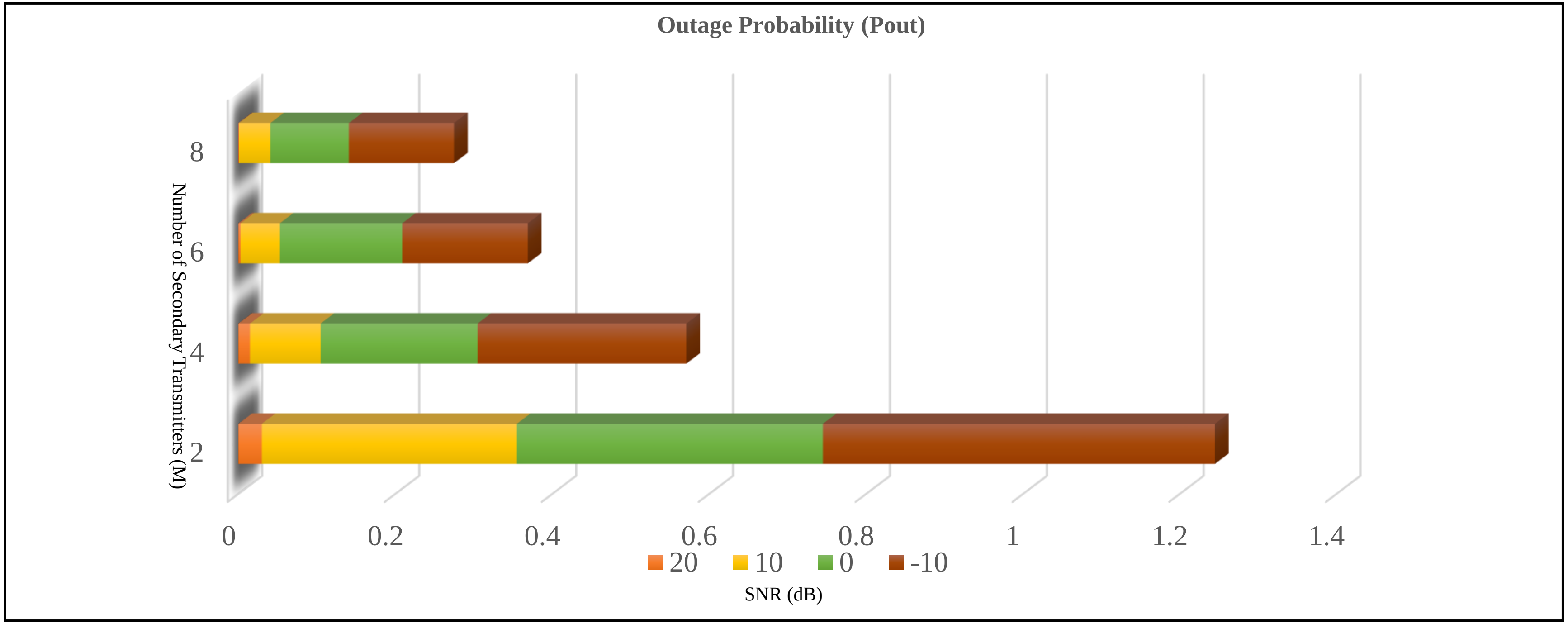


Figure 19



Outage Probability (Pout)
Number of Secondary Transmitters (M)
8
6
4
2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
20
10
0
-10
SNR (dB)

Figure 20

Results

Table 1: Performance Analysis of our model in comparison with the base model on three parameters - Outage Probability, Throughput and Energy

	Base Model	Our model	
Metrics obtained (at Secondary receiver)		Rayleigh	Nakagami
Outage Probability at 0dB (vs SNR)	NA	0.323	0.1627
Throughput (bps) (Maximum)	0.35	0.333	0.333
Energy (Joules) (Maximum)	0.6	0.23	0.7124

Table 2: Variation in Outage Probabilities with the simultaneous variations in both α and Distance.

	Reflection Coefficient(α)				Number of Secondary Transmitters
	0.25	0.5	0.75	1	
Outage Probability	0.3	0.33	0.38	0.534	2
	0.15	0.18	0.19	0.22	4
	0.14	0.15	0.156	0.16	6
	0.135	0.143	0.15	0.153	8

Table 3: Variation in Outage Probabilities with the simultaneous variations in both M and Distance.

	Distance (m)				Number of Secondary Transmitters
	0.1	0.2	0.3	0.4	
Outage Probability	0.15	0.28	0.35	0.38	2
	0.08	0.15	0.18	0.19	4
	0.05	0.1	0.14	0.15	6
	0.04	0.06	0.07	0.08	8

Discussions

Comparisons with original model

1) The backscatter communication network used in the base paper uses all the ‘N’ secondary transmitters to transmit at the same time in backscatter mode and averages the resultant outage probability, channel capacity among other parameters.

   In our model, we utilise the concept of multiplexing, thereby introducing novelty. Our motive is to attempt to use TDMA to allow one one secondary transmitter to transmit to the secondary destination by dividing it into time slots. We perform our parameter analysis by using the equation derived in our definition.

Discussions

Interpreting the simulations

2) We observe the variation of outage Probability with distance. In that plot that we observed, it can be interpreted that the Outage Probability keeps increasing till a certain optimal distance is reached after which the Probability starts to decrease.

3) The throughput also follows the inverse relation and keeps decreasing till it reaches a certain minima where inflection takes place. The range of throughput is indicated as 0.3156 - 0.3333 bps

4) The energy efficiency vs distance plot shows us that maximum energy is obtained at two particular distances from the PT = 0.1 and 0.99 m.

Discussions

Interpreting the simulations

5) We also observe the variation of outage Probability with the number of Secondary Transmitters as this is vital to deciding system capacity. The plots for Outage Prob variation with SNR, distance and Reflection Coeff. keeping the other respective parameters constant help us understand the system complexities better.

6) We also derive the plots for all these parameters for the Nakagami - m fading channel. The shape parameters that categorise this channel have been obtained till a maximum value of 5 for practical purposes.

7) We observe that the Energy Output (averaged over varying values of shape params) - 0.7124J is higher than that of Rayleigh, thus yielding a more energy efficient model. – 0.23 J

Conclusions

1) A comprehensive study of outage analysis has been performed to study the variations of Outage Probability, Throughput and Energy Efficiency with SNR, Reflection Coefficient and distance respectively.
2) The study involved obtaining the mathematical derivations for Outage for the two channel models from scratch - and using it to analyse our system model.
3) Our results indicate that our model is superior in terms of Energy Output but lacks on the Throughput.
4) We also observer that increasing the number of users in the secondary Transmitters leads to a decrease in the Outage, thereby leading to a limit on the number of secondary users.

Future scope

1) TDMA has been explored to inject a different form of transmission scheme. This also opens the scope for the possibilities of exploring other multiplexing schemes like NOMA, FDMA etc. to yield more throughput.
2) In addition, we obtain results for Rayleigh and Nakagami channel models. This takes into account only LOS communication and NLOS communications. However, from our results, we observe that the Outage is more for a Rayleigh model and Energy more for the nakagami model. So, we need to establish a channel model that is a combination of these two - could involve a model similar to Weibull distribution (combination of exponential and higher orders of x)

References

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