Large Scale Fading effect on the Probability of Conjunction in EMI evaluation

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***Abstract*—Probability of conjunction is the new idea for evaluating the electromagnetic interference among different systems. The idea is based on the space object conjunction methodology which mainly focuses on the randomness in the position of the objects. From the EMI perspective, there are some other uncertainties like small- and large-scale fading which can affect the probability of conjunction. In this paper, we investigated the effect of large-scale fading (shadowing) on the EM conjunction probability. The simulation is done using the Monte-Carlo method due to the analytical complexity of the model. From the results, it is concluded that the increase in the standard deviation of the shadowing will cause an increase in the deviation of the probability of conjunction, as compared to the one evaluated by using free space propagation model.**

***Keywords*— Inter-system EMI evaluation, EM conjunction probability, stochastic EMI evaluation, spectrum management, space object conjunction method, shadowing**

I. INTRODUCTION

The ability of a device, unit of equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment is termed as electromagnetic compatibility of that system. Electromagnetic interference (EMI) can be viewed as a kind of environmental contamination which can have consequences that are comparable to other natural effluences like vehicle exhaust emissions or other discharges into the environment. The electromagnetic spectrum is a natural resource which has been progressively tapped by man over the last century. Modern life has come to depend heavily on systems that use the electromagnetic spectrum and its protection is in the interests for all [1]. It is pertinent to mention that the EMC problem is likely to occur if the interfering and interfered devices are physically close to each other, using similar frequencies and operating at the same time. Existing literature and available books focused on EMC, mainly consider the design aspects of electronic circuits and printed circuit boards (PCBs), noise, grounding, shielding, cabling and filtering [2-3]. These types are related to the intra-system EMI evaluation. Fig. 1 shows the possibility of EMI occurrence in the domains of frequency, location and time of operation of the devices.

Baqar et al. [4] gave the novel idea of space conjunction utilized for the intersystem EMC/EMI evaluation, in which the probability of possible conjunction between the systems is evaluated based on the theory of space orbital conjunction. The systems/platforms are assumed to be in an orbit having different orbital parameters like their position, time, the frequency of operation, perturbations in position, and EM size (discussed in a later section of this paper). The analytical description of the conjunction model is formulated by finding the probability of conjunction based on these orbital parameters. The analytical solution was validated through the Monte-Carlo simulations. The receiver threshold was assumed high i.e. the saturation level was taken as the threshold of the receiver, which makes the EM size small. The EM size of the transmitter increases as the transmitted power increases or the sensitivity threshold of the receiver decreases. The perturbations in the positions have a significant effect on the conjunction probability if the EM size of the transmitter is small but it becomes less significant as the EM size increases and in this situation the conjunction probability changes swiftly from 0 to 1, if both systems are approaching each other.

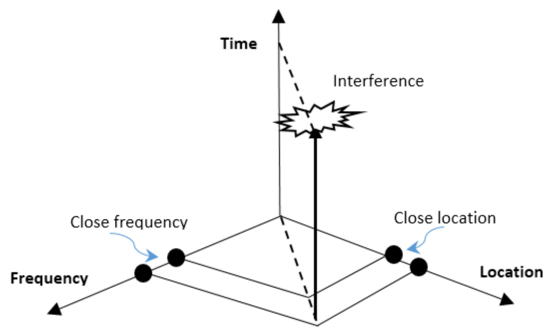

Fig. 1. Interference generated by locations, frequency and operating time

II. CONJUNCTION MODEL

The conjunction prediction of any system is associated with its conjunction parameters [5]. These conjunction parameters or orbital parameters for the EMI evaluation can be written as $O(x, y, z, t, f_c, PD, \psi)$. The parameters are $P(x, y, z)$—system's position, t—the time of operation, f_c—operational frequency, PD—power density, and ψ—spatial coverage (directional or omnidirectional) [4]. The state vector (position and velocity) of system-1 (S_1) is Ω_1 with the covariance matrix C_1 and the state and covariance vectors, Ω_2

and C_2 of for system-2 (S_2) are known at t_{10}, t_{20} respectively. Since we intend to find the probability of conjunction at time t, the corresponding state and covariance matrix at time t would be $\Omega_1(t)$, $\Omega_2(t)$, $C_1(t)$, and $C_2(t)$ respectively. The safety EM power radii of the model is $R_{t_{EM}}$ [5]. These above mentioned parameters are used to evaluate the P_{cEM}, which is considered as a substantial parameter in finding the occurrence of electromagnetic conjunction. The trajectory estimation (mean position) of the model and its associated covariance matrix must be computed accurately as it may cause false alarms in the P_{cEM} calculation. Let us first consider the free space propagation model. The radius of the power contour of the transmitter depends upon the threshold of the receiver (η_r. If the operating frequency, transmitter and receiver antenna gains, are known, we can find the transmitter radius ($R_{t_{EM}}$) as follows

$$R_{t_{EM}} = \left(\frac{c}{4\pi f}\right)\sqrt{\frac{P_t G_t G_r}{\eta_r}} \tag{1}$$

where, P_t is the transmitted power, η_r is the threshold limit of the receiver system. G_t, G_r are the antenna gains of the transmitter and the receiver, respectively, f is the operating frequency, and c is the velocity of EM wave. Using the expression of conjunction model, we can write the probability of conjunction as [6].

$$P_{cEM} = \iiint_V f(X)\,dxdydz \tag{2}$$

V is the volume of the overlap region of the distributions, Since the power contour from the ideal omni-directional antenna is a sphere with $R_{t_{EM}}$ as the radius of the EM power region in which the signal is 100% intercepted or interfered [3]. Therefore, the volume V, swept by the sphere $R_{t_{EM}}$ centered at the transmitter position is given as

$$x^2 + y^2 + z^2 \leq R_{t_{EM}}{}^2$$

For simplification of the model, considering the 2D case, the P_{cEM} can be written as

$$P_{cEM} = \frac{1}{2\pi|C|} \iint_{x^2+y^2 \leq R_{t_{EM}}{}^2} exp\left[-\frac{1}{2}(\mathbf{x}-\boldsymbol{\mu})^T C^{-1}(\mathbf{x}-\boldsymbol{\mu})\right] d\mathbf{x} \tag{3}$$

where,

$$\mathbf{x} = \begin{pmatrix} x \\ y \end{pmatrix}$$

$$\boldsymbol{\mu} = \begin{pmatrix} \mu_{x_2}(t) - \mu_{x_1}(t) \\ \mu_{y_2}(t) - \mu_{y_1}(t) \end{pmatrix}$$

$\boldsymbol{\mu}$ is the relative mean position coordinates of two systems and

$$C = \begin{bmatrix} \sigma_{x_2}{}^2(t) + \sigma_{x_1}{}^2(t) & 0 \\ 0 & \sigma_{y_2}{}^2(t) + \sigma_{y_1}{}^2(t) \end{bmatrix}$$

C is the associated covariance matrix of the distribution. It is assumed that the position errors of both systems are independent to each other and having zero correlation. Therefore, the covariance of the relative position of the systems is the summation of the position error covariance of the individual system.

III. PROBLEM STATEMENT

As discussed earlier in section-II, Equation (3) is used to evaluate the probability of EMI conjunction in free space propagation scenario. The detailed analytical solution of this model is given in [5]. The free space model does not consider the effect of the environment. If any kind of obstruction between the transmitter-receiver (Tx-Rx) is assumed, the same Tx-Rx separation may have a different value of the received power. This effect is called the shadowing and it is defined by adding log-normal randomness in the propagation model. Considering the unity gain antenna for transmitter and receiver, the received power can be written as [7].

$$P_r = P_t - 20\log(f) - 20\log\left(R^*_{t_{EM}}\right) - 32.5 + X_\sigma \tag{4}$$

where, X_σ is a zero-mean Gaussian distribution random variable in dB. P_r and P_t are in dBm, f in GHz and $R^*_{t_{EM}}$ is the threshold radius in m. The * shows that, it as a random variable. We can also write (4) to find the value of $R^*_{t_{EM}}$ as below

$$R^*_{t_{EM}} = 10^{\left(\frac{P_t - \eta_r + 20\log(f) - 32.5 + X_\sigma}{20}\right)} \tag{5}$$

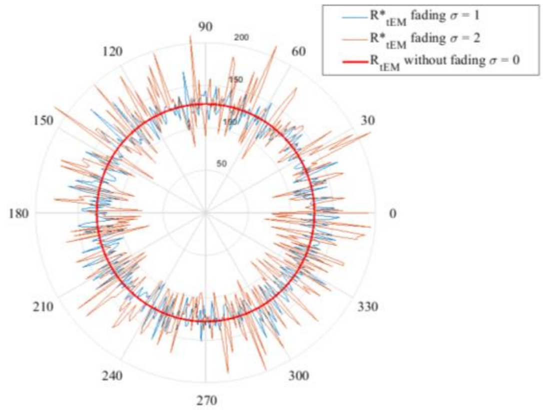

Fig. 2. Effect of randomness in $R_{t_{EM}}$ with two different shadowing level $\sigma = 1$ dB, $\sigma = 2$ dB

$R^*_{t_{EM}}$ is a random variable having a probability density function which is hard to evaluate analytically. Fig. 2 shows the randomness in the EM radius for two different fading levels ($\sigma = 1dB$ and $\sigma = 2dB$). The red circle shows the EM threshold radius calculated using free space propagation model in (1). Due to these randomness in the radius, the analytical solution of the $P_{c_{EM}}$ in (3) is cumbersome as the integral limits become a random variable. However, we can write, $P_{c_{EM}}$ in (3) as an equivalent expression of the probability that the random distance between transmitter & receiver is less than $R^*_{t_{EM}}$. Mathematically,

$$P_{c_{EM}} = \Pr[Y < R^*_{t_{EM}}] = \int_{-\infty}^{R^*_{t_{EM}}} f_Y(y)dy \tag{6}$$

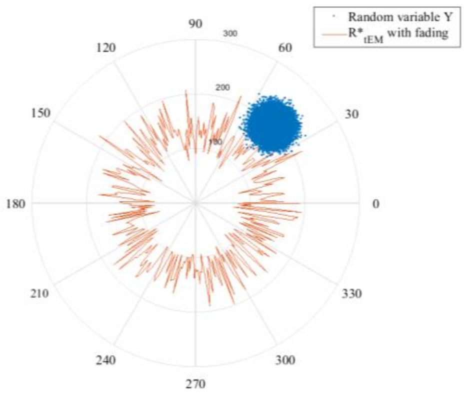

Fig. 3. Randomness in EM size ($R_{t_{EM}}^{*}$) and randomness in the relative distance between two systems (random variable Y)

where, $f_Y(y)$ is the probability density function of the relative distance Y of two random points, which follows the Rayleigh distribution, since the randomness in the position is assumed bivariate Gaussian [8]. $R_{t_{EM}}^{*}$ is the random threshold radius due to the log-normal fading. Fig. 3 illustrates the depiction of the problem. Since, the conjunction model is primarily based on the relative random distance of the systems, the random distance Y can to be converted to the new random variable Z which can be written as,

$$Z = \frac{Y}{\sqrt{X_\sigma{}^*}} \tag{7}$$

$X_\sigma{}^*$ is the shadowing level in normal units (not in dB) i.e.

$$X_\sigma{}^* = 10^{\left(\frac{X_\sigma}{10}\right)}$$

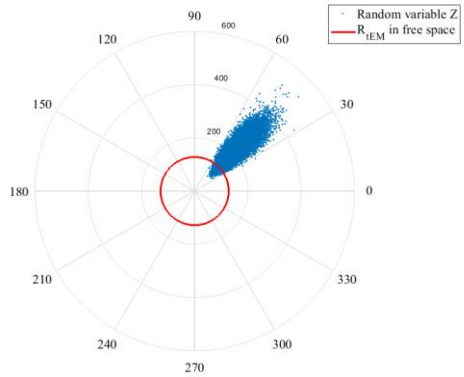

Fig. 4. Randomness in EM size is merged to form a new random variable Z

The probability of conjunction with shadowing influence can be written as

$$P_{c_{EM}} = \Pr[Z < R_{t_{EM}}] = \int_{-\infty}^{R_{t_{EM}}} f_z(z)dz \tag{8}$$

The shadowing effect is incorporated in the randomness of the relative distance and new random variable Z is formed The $R_{t_{EM}}$ is now become a deterministic variable which is the threshold radius in free space and can be evaluated by using expression given in (1). Equation (8) is the equivalent analytical expression for finding the probability of conjunction in the presence of large-scale fading. Fig. 4 shows the equivalent representation of the scenario in Fig. 3, where the random variable Y is changed to the random variable Z and making EM size a deterministic value. However, the probability density function of Z is hard to formulate analytically. So we can use the Monte-Carlo method to evaluate $P_{c_{EM}}$. The simulation scenario and results are discussed in the next sections.

IV. Simulation Scenario

We assumed that the simulation scenario consists of a transmitter and a receiver system where the transmitter is located at the origin and receiver system is approaching towards the transmitter from a fixed direction (θ). The randomness in their positions is taken as bivariate independent Gaussian variable with zero mean and variances $\sigma_x{}^2, \sigma_y{}^2$ respectively. Perturbations in the positions of both systems are assumed equal. The operating frequency is taken as 5.9 GHz and transmitter maximum power is assumed 20 dBm while the receiver threshold is taken as -70dBm. Pseudo code of the Monte-Carlo simulation is given as

START
Set $(x_t, y_t) = (0,0)$
Set $(x_r, y_r) = (d\cos\theta, d\sin\theta)$
where,
    $\theta\ (fixed) \in$ U $[0,2\pi]$ and $d \in [d_{min}, d_{max}]$ (d is mean relative distance)
find $R_{t_{EM}}$ using (1)
for $d \rightarrow d_{min}$ to d_{max}
    generate bivariate Gaussian samples of (x_t, y_t) & (x_r, y_r)
    find relative distance Y of random points
    If $Y < R_{t_{EM}}$
        count=count+1;
    Pr = count /total samples; ($P_{c_{EM}}$ without fading)
    find received power at Y using (1)
    add X_σ log-normal random shadowing effect using (4)
    evaluate random variable Z using (1)
    If $Z < R_{t_{EM}}$
        count=count+1;
    Pr_{fading} = count/total samples; ($P_{c_{EM}}$ with fading)
    END
END

V. Results & Discussions

The shadowing effect on the probability of conjunction is shown in Fig. 5. Each probability curve corresponds to the σ values from 0 to 9 dB. It can be seen that the effect of fading is not uniform over the entire trajectory scenario. It depends on the mean relative distance of the systems. In our particular scenario, where the receiver is approaching towards the transmitter, the fading effect is maximum at the extreme positions of receiver system. It is worth noting that the effect of log-normal shadowing is minimum at the relative distance where the probability of conjunction in free space (without fading) is around 0.5. In our scenario, the relative distance is around the threshold radius i.e. $R_{t_{EM}}$. But we cannot generalize the statement that 0.5 probability always occurs around $R_{t_{EM}}$. Since, it also depends on other parameters i.e. threshold radius, mean and variance of the position. Moreover, it can also be seen that at any particular distance, the increase in σ value shows the increase in the deviation of $P_{c_{EM}}$ from the non-faded channel $P_{c_{EM}}$. Fig. 6 shows the simulation results with change in the standard deviation of the position error. In Fig. 5 σ_x, σ_y is taken $10m$ while In Fig. 6, it is assumed $30m$. This shows that the fading effect in $P_{c_{EM}}$ changes with the change in the conjunction parameter σ_x or σ_y.

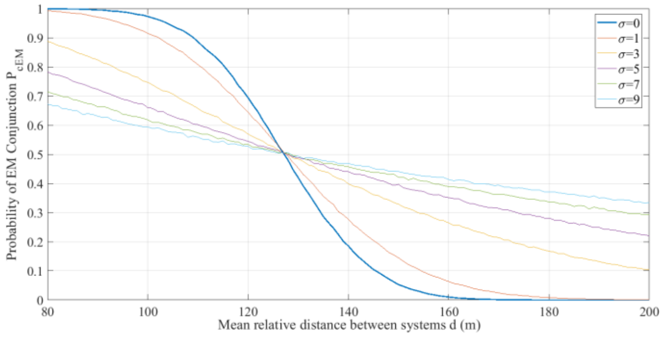

Fig. 5. $P_{c_{EM}}$ vs relative distance of the systems having different levels of shadowing at $\sigma_x = \sigma_y = 10m$

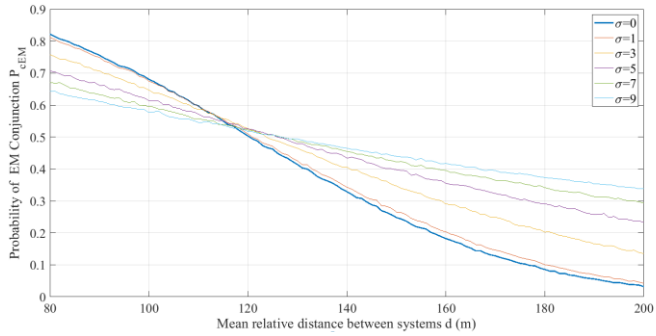

Fig. 6. $P_{c_{EM}}$ vs relative distance of the systems having different levels of shadowing at $\sigma_x = \sigma_y = 30m$

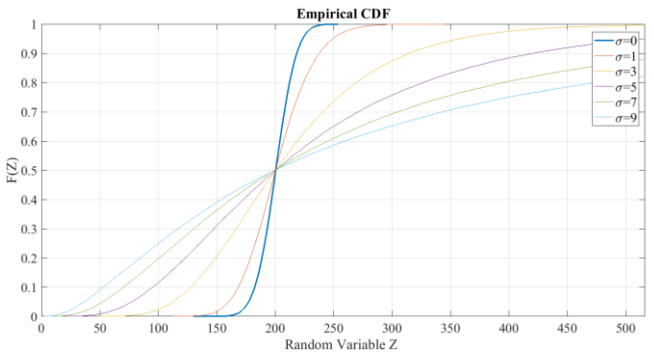

Fig. 7. CDF of the random variable Z at $200m$ with $\sigma_x = \sigma_y = 10m$

Fig. 7 shows the empirical CDF of the random variable Z which corresponds to the randomness in $R_{t_{EM}}$ fused with the randomness in the relative distance of the systems. CDF curves are shown for different level of fading at the receiver position of $200m$. The slope of the CDF curve is decreasing with the increase in the standard deviation of the log-normal shadowing. The probability of conjunction in (8) can easily be computed by the CDF curves.

VI-Conclusion

The conjunction methodology is used in space orbital conjunction from three or more decades for the collision risk assessment. From the electromagnetic perspective, there are many factors that have an impact on the probability of EM conjunction. The perfect EM collision occurs if the probability of conjunction is 1. With changing the orbital parameters i.e. EM radius, mean & variance of the position and EM environment, the conjunction probability also changes. We presented the effect of large scale fading on the probability of conjunction and focused on the evaluation method. The effect of fading cannot be generalized quantitatively as it depends on the defined simulation scenario. But we can conclude that fading is also one of the parameter that cannot be ignored. By increasing the shadowing level, the deviation of $P_{c_{EM}}$ from the non-faded $P_{c_{EM}}$ also increases. Hence, for the environment having large fading sigma, the deviation is high. Furthermore, the Mont-Carlo simulation method is used for the evaluation of $P_{c_{EM}}$ in such scenarios rather than the analytical solution. The method and results are helpful in the stochastic modelling for the EMI evaluation, where the actual position of the transmitter and receiver is non deterministic.

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