Presentation of an Algorithm for Secure Data Transmission based on Optimal Route Selection during Electromagnetic Interference Occurrence

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Article Info	ABSTRACT
	This paper proposes a comprehensive algorithm for secure data transmission via communication conductors considering route optimization, shielding and data authentication. Using of appropriate coding method causes more efficiency for suggested algorithm during electromagnetic field attack occurrence. In this paper, MOM simulation via FIKO software is done for field distribution. Due to critical situation of malfunctioning of data transferring, appropriate shield is designed and examined by shielding effectiveness (SE) criterion resulted of MOM simulation; finally to achieve reliability of data security, MAC hash function is used for space with field attack probability, turbo code is employed.

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1. INTRODUCTION

As digital systems move to ever increasing operating frequencies. Electromagnetic interference (EMI) gets increasingly difficult to predict [1], [3]. Analytical methods have been developed to estimate EMI by closed formals [2], [4], [5]. To achieve electromagnetic compatibility (EMC), conducted emissions from switching power converters, circuit breaker, and etc. Should comply with the EMI regulatory limits [6-9]. Due to the results susceptibility investigations in combination with the known capabilities of available intentional electromagnetic interference (IEMI) sources, it become obvious that it is necessary to protect critical systems and infrastructure [10-12]. In Cyber-Physical Networked System (CPNS), there are two main aspects: EMI and False data injection [13]. so, for designing a system with attack probability optimized route selection to achieve maximum ability against EMI must be provided for a cavity with transmission conductors, appropriate route selection can be done via Analytical Hierarchy Process (AHP), Fussy AHP, Artificial Neural Network (ANN), etc. the AHP approach is a flexible but Well-Structured methodology to analyze and solve complex decision problems by structuring them into a hierarchical framework [14-16]. An important parameter of AHP criteria for route selection in proposed problem is EMI. So using suitable numerical method should be employed. Numerical techniques. e.g... FDTD. Method of Moments (MOM) and hybrid methods have been applied as general solutions to arbitrarily shaped apertures, achieving excellent agreement with measurements. Among all of these numerical techniques. MOM is especially efficient for solving open-space radiation problems [17-20]. Therefore flux distribution in a cavity is obtainable as input parameter of safe route selection.

Also, the shielding efficiency of an enclosure is specified by the Shielding Effectiveness (SE), defined as the ratio of the electric/magnetic field at an observation point without and with the enclosure[17], [21-27]. To achieve move security use of turbo codes in Physical-layer Network Coding (PNC) system to ensure reliable communication is suggested. However, for more contribution Bit-Error-Rate (BER) performance for proposed problem mast be simulated [2830]. Findlay, Message Authentication Code (MAC) hash function are a suitable method for data authentication during false data infection [31-34]. In this paper, an enclosure including transmission conductor is studied during IEMI. Firstly by using of MOM, field simulation will be done with the help of FIKO software, secondly, field distribution is given to input data for weighting of AHP method. After Route Selection of Communication Conductor, Coding and Authentication technique is applied as a contribution of comprehensive approach. For proposed IEMI of CPNS.

2.   CALCULATIONS AND SIMULATIONS FOR FIELD DISTRIBUTION:

Preliminaries of shielding effectiveness calculation via MOM formulation. In this section, Shielding Effectiveness (SE) calculation for enclosure system is discussed. Firstly, MOM formulation is given. Then, SE formula for enclosure and cavity is explained. Finally, for investigated enclosure, field via MOM simulation software is done.

2.1. MOM Simulation

To apply the boundary condition for the electric field calculation on the surface of the sample enclosure, the integral equation is used as below [17].

$$\hat{n} \times (\vec{\vec{G}}_{EM}^o \otimes \vec{M}_R + \vec{\vec{G}}_{EJ}^o \otimes \vec{J}_S + \vec{\vec{G}}_{EM}^o \otimes \vec{J}_{ext}) \qquad \begin{cases} \vec{M}_R, & in\ the\ aperture\ region \\ \\ 0, & elswhere \end{cases} \qquad (1)$$

Symbol $\otimes$ shows the convolution product for integral operation; $\vec{\vec{G}}_{EJ}^o$ *and* $\vec{\vec{G}}_{EM}^o$ are the electric dyadic Green's functions excited by the magnetic and electric current densities in the free space, respectively; and $\hat{n}$ is the outward unit vector normal to the enclosure's surface. The electric field $\vec{E}_{ext}$ at the position of the excitation/observation $(\vec{J}_{ext})$ and magnetic field $\vec{H}_R$ on the exterior surface of the aperture were calculated using the below integral formula:

$$\begin{bmatrix} \vec{E}_{ext} \\ \vec{E}_R \end{bmatrix} = \begin{bmatrix} \vec{\vec{G}}_{EM}^o & \vec{\vec{G}}_{EJ}^o & \vec{\vec{G}}_{EJ}^o \\ \vec{\vec{G}}_{HM}^o & \vec{\vec{G}}_{HJ}^o & \vec{\vec{G}}_{HJ}^o \end{bmatrix} \otimes \begin{bmatrix} \vec{M}_R \\ \vec{M}_S \\ \vec{M}_{EXT} \end{bmatrix} \qquad (2)$$

$\vec{\vec{G}}_{HM}^o$ *and* $\vec{\vec{G}}$ Are the magnetic dyadic Green's functions excited by the magnetic and electric current densities in the free space, respectively. So, for electromagnetic distribution for a cavity with circular or rectangular aperture a Mined Potential Integral Equation (MPIE) as below formula must be solved;

$$\hat{n} \times \begin{pmatrix} -\frac{1}{\varepsilon}\left(\nabla \times \vec{\vec{G}}_F^o\right) \otimes \overrightarrow{M_R} - j\omega\vec{\vec{G}}_A^o \otimes \vec{J}_S - \frac{j}{\omega}\nabla\left(G_\psi^0 \otimes \nabla.\vec{J}_S\right) \\ -j\omega\vec{\vec{G}}_A^o \otimes \vec{J}_{ext} - \frac{j}{\omega}\nabla\left(G_\emptyset^0 \otimes \nabla.\vec{J}_{ext}\right) \end{pmatrix} = \begin{cases} \vec{M}_R, & in\ the\ aperture\ region \\ \\ 0, & elswhere \end{cases}$$

$$(3)$$

$$\begin{cases} \vec{E}_{ext} = -j\omega\vec{\vec{G}}_A^o \otimes [\vec{J}_{ext} - \vec{J}_S] - j\omega\vec{\vec{G}}_A^o \otimes \vec{J}_S - \frac{j}{\omega}\nabla(G_\psi^0 \otimes \nabla.[\vec{J}_{ext} - \vec{J}_S]) + \varepsilon\left(\nabla \times \vec{\vec{G}}_F^o\right) \otimes \overrightarrow{M_R} \\ \vec{H}_R = -j\omega\vec{\vec{G}}_F^o \otimes \overrightarrow{M_R} - \frac{j}{\omega}\nabla(G_{\emptyset_m}^0 \otimes \nabla.\overrightarrow{M_R}) + \frac{1}{\mu}\left(\nabla \times \vec{\vec{G}}_A^o\right) \otimes [\vec{J}_{ext} - \vec{J}_S] \end{cases}$$

Using MOM [1] for field distribution of the surface of the enclosure with aperture both exterior and interior, provide MPIE is solved. In this way, mesh cells must be created by dividing the surface of enclosure. Then electric and magnetic current densities distribution should be computed that they can be expanded in terms of Vector Roof-Top basic function [17].

$$\vec{J}_{ext}(\vec{r}) = \sum_n a_n^{ext} \vec{f}_n(\vec{r})\ on\ surface\ of\ excitation \qquad (4)$$

$$\vec{J}_S(\vec{r}) = \sum_n a_n^s \vec{f}_n(\vec{r})\ on\ enclosure\ surface \qquad (5)$$

$$\vec{M}_R(\vec{r}) = \sum_m \vec{f}_m(\vec{r}) \text{ on aperture surface} \tag{6}$$

Where $a_1^{ext}, a_e^{ext}, \dots, a_n^{ext} \dots$ and $a_1^s, a_e^s, \dots, a_n^s \dots$ are the expansion coefficients of the electric current densities on the surfaces of the exterior excitation and the enclosure, respectively.

2.2. Shielding Effectiveness Evaluation

To achieve more understanding of Electromagnetic Interference (EMI) problem and it's definition, shielding effectiveness is computed [21-25]:

$$SE_E = 20 \log_{10} \left| \frac{E_i}{E_t} \right| \, dB \tag{7}$$

$$SE_B = 20 \log_{10} \left| \frac{H_i}{H_t} \right| dB \tag{8}$$

SEE and SEB is different for near field, but they have the some value for field. SE coefficient is related to frequency, field type, field incident direction to shield, field measurement region in the shield, Geometric configuration, and shield raw material. The incident electromagnetic waves is converted to absorption and reflection losses. Also, a small portion can be defined as a correction of reflection factor for multi-reflection modeling. In this way, SE can be formulated as below:

$$SE_{dB} = A_{dB} + R_{dB} + M_{dB} \tag{9}$$

Where A, R and M are the absorption, reflection, and correction of reflection factors.

$$A = 3.34 \, t \sqrt{f \mu_r \sigma_r} \tag{10}$$

Where t is a thickness of shield, μr and σr are relative permeability and relative conductivity.
For $(r \ll \lambda/2\pi)$ Low Impedance loop Antenna:

$$R = 20 \log_{10} \left(\frac{0.0117}{\sqrt{\frac{r \sigma_r f}{\mu_r}}} + 5.35 \sqrt{\frac{\sigma_r f}{\mu_r}} + 0.354 \right) \tag{11}$$

For $(r \gg \lambda/2\pi)$ High Impedance loop Antenna:

$$R = 322 - 20 \log\left(\sqrt{\mu_r f^3 / \sigma_r r}\right) \, (dB) \tag{12}$$

For plan wave Antenna:

$$R = 168 - 10 \log(\mu_r f / \sigma_r) \, (dB) \tag{13}$$

In all equations r is the distance between the source and the Shielded surface. M is the Multiple Correction reflection coefficient and calculated by following equation:

$$M = 20 \log \left[|1 - N \times 10^{\frac{-A}{10}(e^{-0.23A})}| \right] \tag{14}$$

Where N is a complex function that is obtained from below relation:

$$\frac{(1-m^2) - 2m^2 - j2\sqrt{2m} \times (1-m^2)}{\left[1 + (1+\sqrt{2m})^2\right]^2} = Re(N) + JIm(N) \tag{15}$$

m is defined for wave plate as below:

$$m = 9.77 \times 10^{-10} \sqrt{f \mu_r / \sigma_r} \tag{16}$$

2.3. Field Simulation and SE Calculation

A shield with 60 rectangular aperture with dimensions of 2*2 cm and total surface area of 48 cm^2 is considered in Figure 1. For radiated field, field analysis is done during shield is placed above the ground. Presentation of current model for field analysis using MOM technique is proposed.
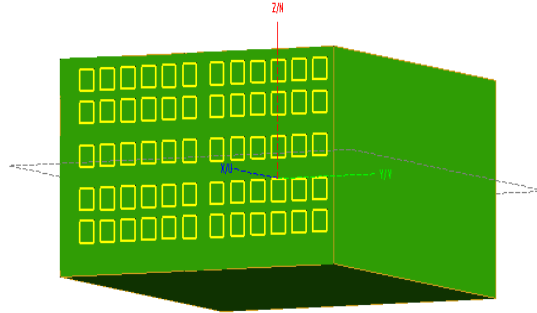

Figure 1. An enclosure with apertures

Field equation can be written as [27], [17], [36]:

$$H_t^o\left(J^{inc}\right)+H_t^o\left(M_s\right)+H_t^o(J^o)=H_t^i\left(-M_s\right)+H_t^i\left(J^i\right) \tag{17}$$

$$E_t^i(-M_s) + E_t^i(J^i) = 0 \qquad\qquad \text{in the enclosure}$$
$$E_t^0(J^{inc}) + E_t^0(M_S) + E_t^0(J^0) = 0 \qquad \text{out of the enclosure} \tag{19}$$

The above equation is solved using MOM. By considering below relation:

$$\boldsymbol{M}_s = \sum_{n=1}^{N_M} \gamma_n \boldsymbol{M}_n \tag{20}$$

$$\boldsymbol{J}^o = \sum_{n=1}^{N_o} \alpha_n \boldsymbol{J}_n^o \tag{21}$$

$$\boldsymbol{J}^i = \sum_{n=1}^{N_i} \beta_n \boldsymbol{J}_n^i \tag{22}$$

Set of solving equations are:

$$H_t^o(J^{inc}) + \sum_{n=1}^{N_m} \gamma_n H_t^o(M_n) + \sum_{n=1}^{N_0} \alpha_n H_t^o(J_n^o)$$
$$= \sum_{n=1}^{N_m} \gamma_n H_t^i(-M_n) + \sum_{n=1}^{N_i} \beta_n H_t^i(J_n^i) \tag{23}$$

$$E_t^o(J^{inc}) + \sum_{n=1}^{N_m} \gamma_n E_t^o(M_n) + \sum_{n=1}^{N_0} \alpha_n E_t^o(J_n^o) = 0 \tag{24}$$

$$\sum_{n=1}^{N_m} \gamma_n E_t^i(-M_n) + \sum_{n=1}^{N_i} \beta_n E_t^i(J_n^i) = 0 \tag{25}$$

However, solving of the above equations is related to solving of Somerfield integral [27], [17], [36]:

$$\int_0^\infty f(k_\rho) \frac{k_\rho}{jk_z} e^{-jk_z|z|} J_0(k_\rho\rho)dk_\rho \tag{26}$$

Or simple of the as:

$$\frac{e^{-jkr}}{r} = \int_0^\infty \frac{k_\rho}{jk_z} e^{-jk_z|z|} J_0(k_\rho\rho)dk_\rho \tag{27}$$

$$k^2 = k_\rho^2 + k_z^2 \tag{28}$$

Kernel of Somerfield integral is written as:

$$f(k_p) = \sum_{i=1}^M b_i e^{-ja_i k_z} \tag{29}$$

The rapid increase of the SE at low frequencies is quite clear, which indicates the proportions of the aperture and wavelength. Therefore, to start of EMI problem evaluation, the field simulation via MOM technique is done then SE graph for considered frequency range is computed. The results of SE calculation via MOM field simulation are shown in Figure 2.

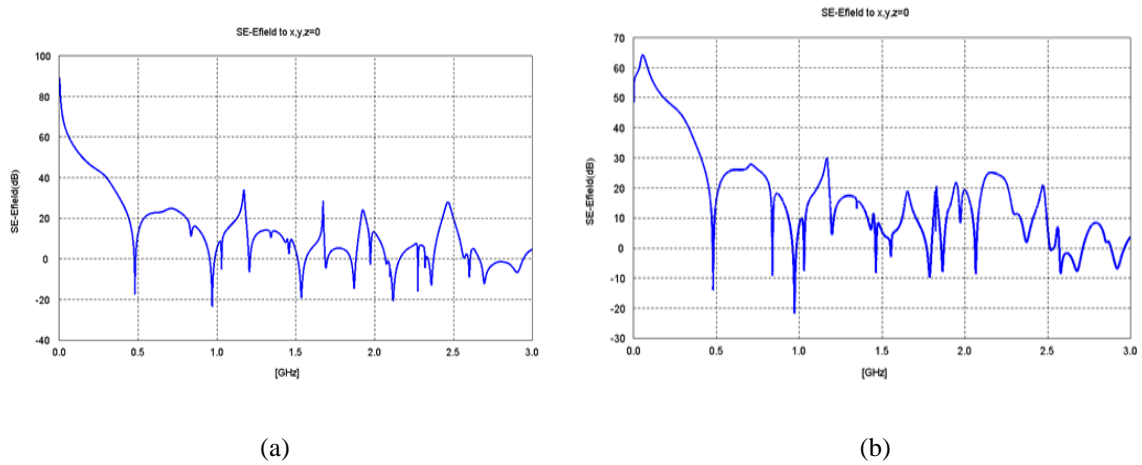(a)   (b)

Figure 2. Show results of SE calculation via MOM field simulation for frequency range 0-3 GHZ for enclosure. (a) With 60 apertures respectively (b) with 36 apertures respectively

3.   ROUTE OPTIMIZATION USING AHP METHOD:

During EMI occurrence, to achieve secure route optimization, main criteria can be found as: EMC, voltage drop and price. Analytical Hierarchy Process (AHP) is a suitable method for discrete decision making [14-16]. In this method after identifying of criteria and alternatives, pair wise comparison matrix for criteria and alternatives regarding to each criterion is obtained via weighting process from formula or knowledge of expert persons. Then normalized eigenvalue vector for each matrix is computed. For deviation from selecting weight, sensitivity analysis can be done. To solve proposed problem, main criteria can be formulated as below:

$$EMC = \sum_{\substack{i=1 \\ j=i+1}}^n \frac{B_{mean_{ij}} - \Delta B_{Shilded\,Cable} - \alpha\Delta B_{Conduit}}{B_{mean_{ij}}} \qquad \alpha = \begin{cases} 1 & B_{mean} \geq B_{Critical} \\ 0 & B_{mean} \leq B_{Critical} \end{cases} \tag{30}$$

Where, B mean i, j is an average field between two considered point i, j that i, j are the start and end point of the route. ΔB shielded cable is the amount of field reduction due to shielding of data transmission cable, and ΔB conduit is the amount of field reduction due to conduit usage. Conduit usage is shown by α factor. Cost is the second criterion which is related to several parameters such as: cable, shield and conduit, route length and installation cost. So, cost can be formulated as:

$$P = \sum_{i=1}^{n} \sum_{j=1}^{n} (P_{cable} + \alpha P_{conduit} + \beta P_{salary}) L_{ij} \qquad \alpha = \begin{cases} 1 & B_{mean} \geq B_{Critical} \\ 0 & B_{mean} \leq B_{Critical} \end{cases} \qquad (31)$$

Where P_{cable}, $P_{conduit}$ **and** P_{salary} are the cost of cable, conduit and salary respectively. **β** Coefficient is defined as variation of the salary of worker which is differing in different country. The third criterion, voltage drop is expressed as:

$$\Delta V_M = \frac{\sum_{i=1}^{t} \alpha_j \Delta V\%}{\Delta V_{base} \times \sum_{j=1}^{t} \alpha_j \times t} \quad , \Delta V\% = \frac{100 \rho L I cos\emptyset}{\alpha} \qquad (32)$$

Where t is the number of variety of conductors. Correction factor, α_j is defined for amount of cable sensitivity to drop voltage regarding to its application. ΔVM is average voltage drop for each selective route. ΔV% is a voltage drop for a conductor with a cross section with ρ, L, I parameters for power factor $cos\emptyset$.

3.1. AHP Implementation for Sample Enclosure

As a case study, a sample enclosure with defined node is considered as shown in Figure 3.

To evaluate EMC, field simulation using MOM technique via FEKO software. Field distribution is shown is Figure 4. According to field simulation, flux density is obtained for each node Table 1. For cabling route from A to J (1 to 12), the most popular probabilistic routes (according to our knowledge) is given in Table 2. Based on previse formula for three criteria EMC, most, voltage drop, the calculation of initial judgment for each popular route is done Table 3. Also, the pairwise comparison matrix for alternatives can be computed regarding to Table 3. then final results is illustrated in Figure 5. If the weight of criteria differ, the sensitivity analysis can be done.
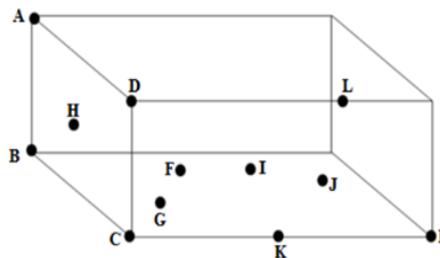

Figure 3. Defined node for sample enclosure for selection of optimized secure route
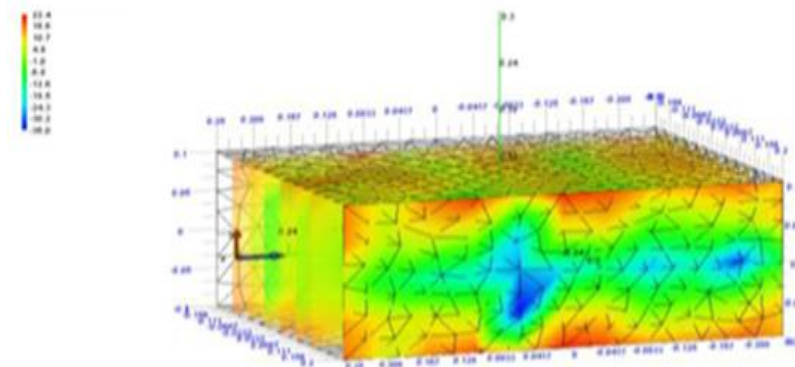

Figure 4. Field simulation for conceptual enclosure

Table. 1. 3-D flux density for each node

node	Coordinate (m)	Flux density(μT)
1	(0.25, -0.2, 0.1)	98
2	(0.25, -2, -0.1)	97.60
3	(0.25, 0.2, 0.1)	83.80
4	(0.25, 0.2, 0.1)	99
5	(-0.25, 0.2, 0.1)	83.10
6	(0.125, 0.2, 0)	6480
7	(0.208, 0.2, 0.05)	71.60
8	(0.25, 0, 0)	117.46
9	(0.04, 0.2, 0)	53.30
10	(-0.22, 0.2, 0)	45.50
11	(0, 0.2, -0.1)	816
12	(-0.04, 0.2, 0.1)	935.30

Table. 2. Possible Routes Between point 1 to 10

	Direction With cross detail
1	1→4→3→7→9→10
2	1→2→3→11→10
3	1→8→3→7→6→9→10
4	1→2→3→7→9→10
5	1→4→9→10
6	1→4→6→9→10
7	1→4→7→9→10
8	1→8→4→12→10
9	1→2→8→6→9→10
10	1→8→3→11→5→10
11	1→8→6→9→ 10

Table 3. Initial judgment of each popular route due to each criteria

	EMC	Voltage drop	cost
1	1.1489	0.0598	3.5732
2	2.2558	0.0546	5.7333
3	1.5827	0.0519	3.1148
4	1.4812	0.0596	3.5732
5	1.9069	0.0448	5.1673
6	1.0330	0.0453	2.7152
7	1.0934	0.0450	2.7017
8	2.4884	0.0472	5.3089
9	1.6162	0.0502	3.0134
10	2.5879	0.0561	6.2161
1	1.1283	0.0402	2.4133

Goal: Optimal Routing of Data Transfer
Overall Inconsistency = .04

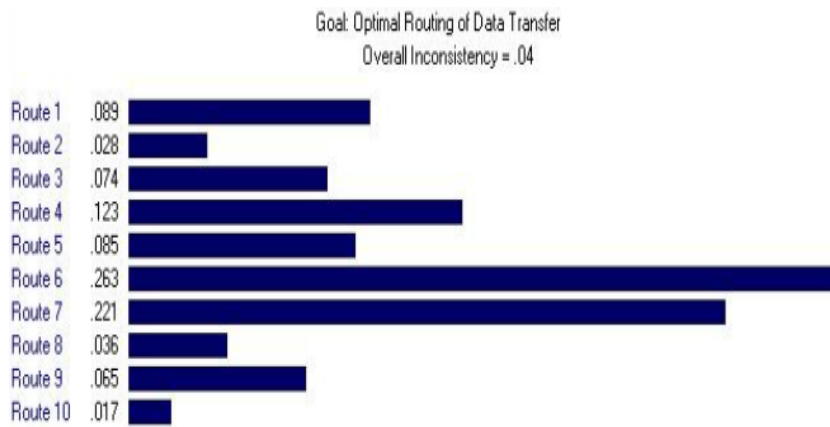| Route 1 | .089 |
Route 2	.028
Route 3	.074
Route 4	.123
Route 5	.085
Route 6	.263
Route 7	.221
Route 8	.036
Route 9	.065
Route 10	.017

Figure 5. Final weight if routes

Pairwise comparison matrix for criteria is written as:

$$G = \begin{bmatrix} EMC & \Delta V & P \\ 1 & 5 & 8 \\ 1/5 & 1 & 3 \\ 1/8 & 1/3 & 1 \end{bmatrix} \tag{33}$$

4.   AUTHENTICATION AND CODING SECONDARY SHIELDING

After secure route optimization and appropriate shielding for conceptual enclosure with apertures, software protection is so crucial. For this aim, one authentication algorithm in the category of Message Authentication Code (MAC) hash function and one coding algorithm based on convolutional code or turbo code must be employed. In this section SM3 and turbo code is studied and applied for our application [35].
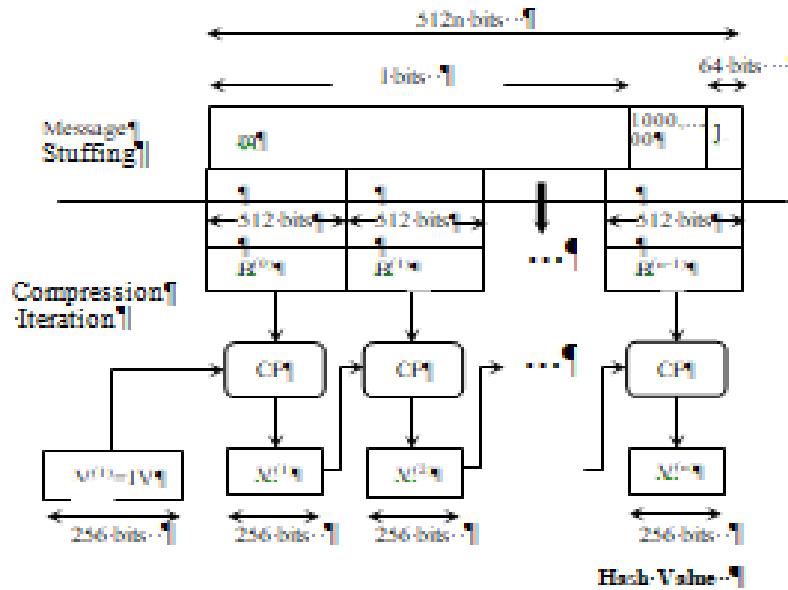
Figure 6. SM3 algorithm

With l (l<264) bits input message m, SM3 hash algorithm generates 256-bit output hash value by message stuffing and compression iteration [35]. The algorithm of this can shown in Figure 6. Also can shown the process of compresssion function in Figure 7.
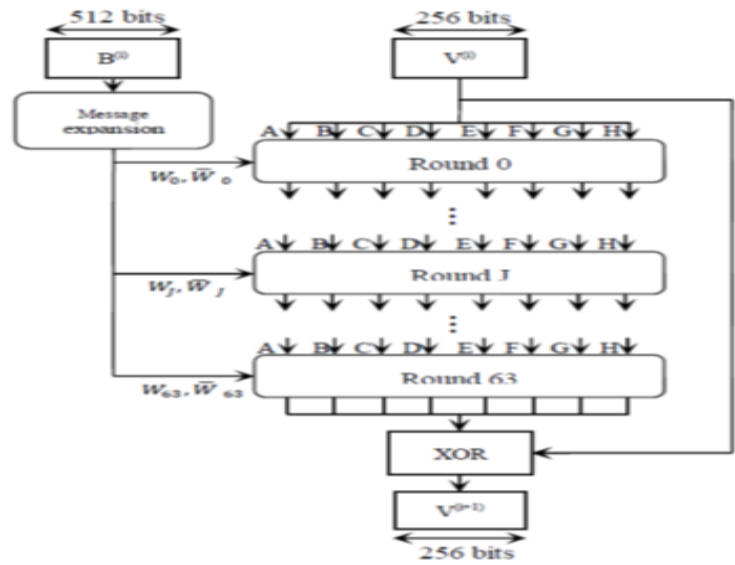

Figure 7. Compresssion function

4.1. TURBO CODE

To create a software shield, a turbo code is used to code the channel. In this paper, instead of using the Viterbi decoders, as the most famous decoder of convolutional codes and turbo code, The MAP method, such as BCJR algorithm, is used. This algorithm is soft-input and soft-output coding. in this paper, to compare and evaluate the effectiveness of the proposed method, The comparison between the Viterbi decoder with the hard-output, soft-output and BCJR algorithm has been performed and the results have been investigated [28], [37]. The complexity of a decoding method is often quantified in terms of the number of operations needed for decoding, which can be described in terms of the number of states or trellis-transitions. Turbo code scheme is introduced in Figure 8 [28], [37].
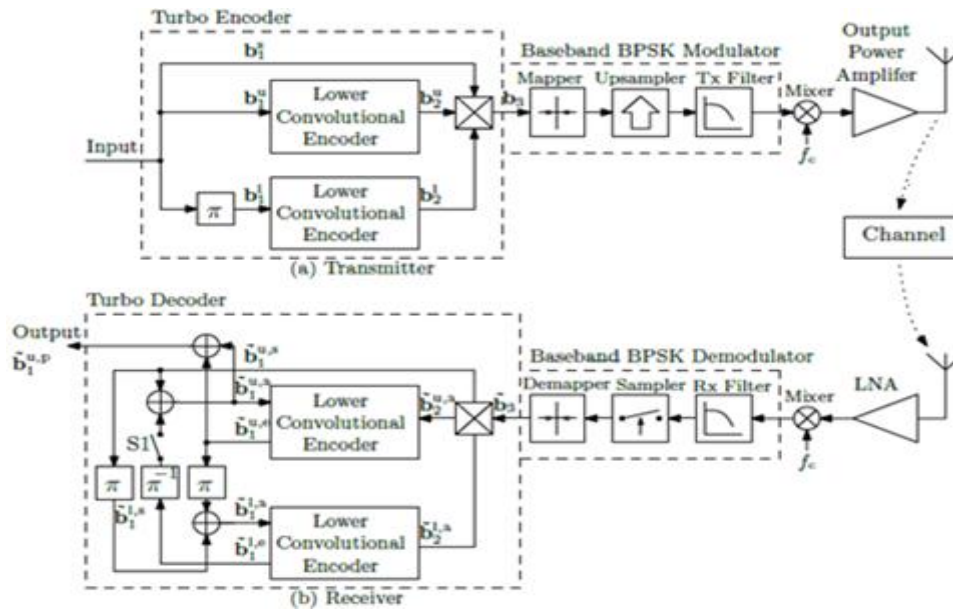
Figure 8. ABPSK- modulated R=1/3 TC scheme

To design coding software protection, BCJR algorithm and Viterbi decoder are implemented by rate 1/3. Result simulation for BER with SNR 0-20 range and by 3 iteration is given in Figure 9. Also the results of bit error rates in terms of SNR and for hard-output and soft-output Viterbi decoder is shown in Figure 10.
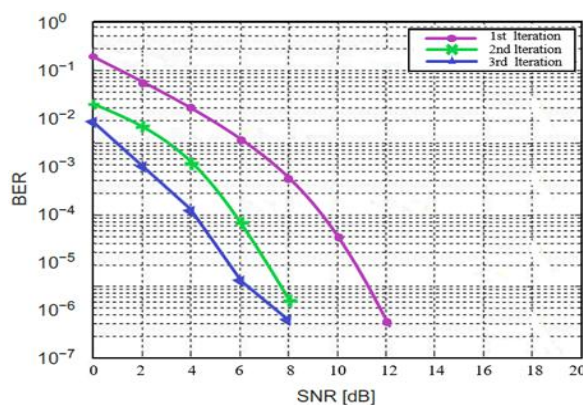

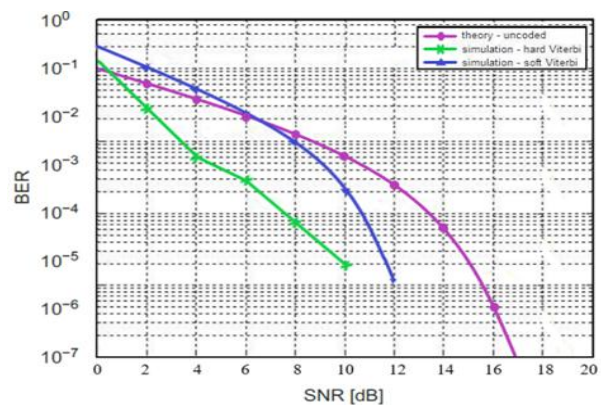Figure 9. BCJR decoder operation simulation

Figure 10. Viterbi decoder operation simulation with 1/3 TC

According to the results and compare them, it is clear that the bit error rate in BCJR algorithm is less than Viterbi. So this algorithm works better as a software protection.

5. ESENTATION OF COMPREHENSIVE ALGORITHM FOR EMI MITIGATION IN ENCLOSURES

In this section, an algorithm for mitigation of EMI in enclosures with apertures is presented as passive defense approach. This algorithm is shown in Figure 11. In this algorithm after the definition of EMI source, Enclosure, Cavity and introduce environment, enclosure material, input parameters, simulation of magnetic fields is done by numerical solution of MOM. Changing the specification of the enclosure and cavity will continue until the desired SE is reached. Then, by considering the three indexes, EMC, voltage drop and price, Optimization of the transmission path is accomplished by AHP Method. Finally, we tried to

use coding with BCJR algorithm to reduce BER. This algorithm will be completed by achieving optimal results and increasing the security of data transmission.
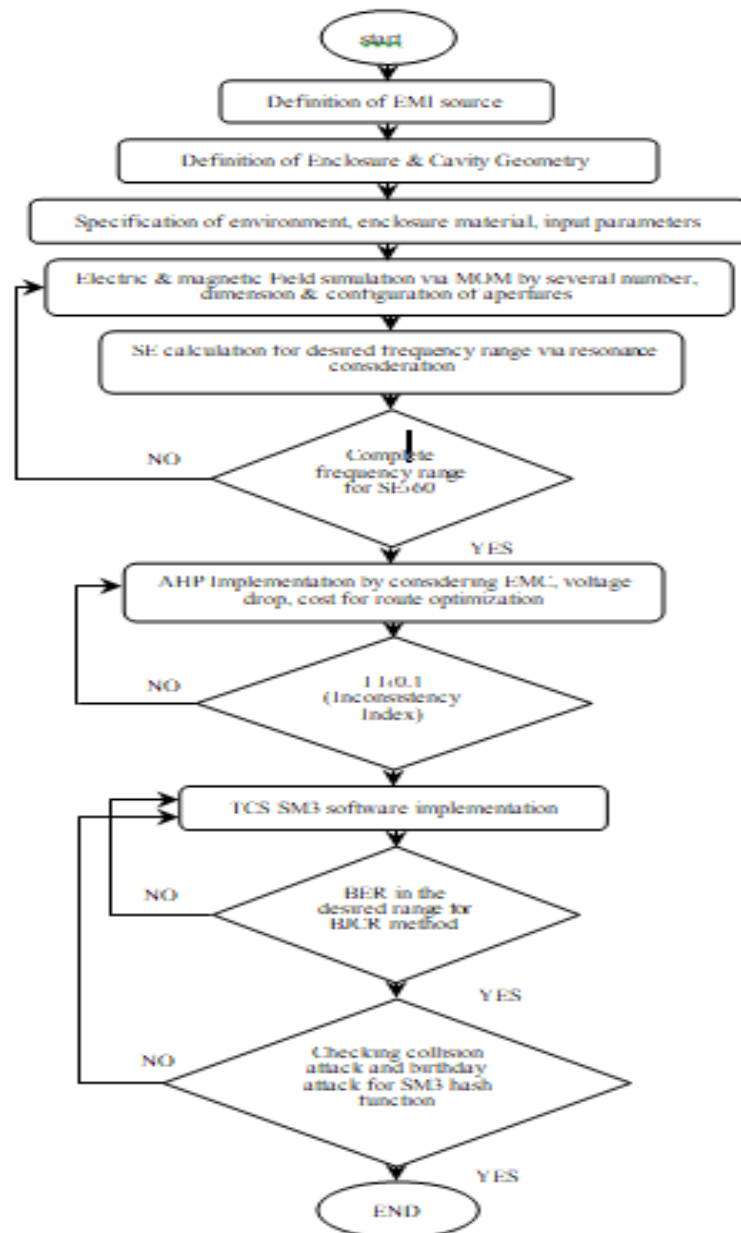

Figure 11. Algorithm for mitigation of EMI in enclosures with apertures is presented as passive defense approach

6.   CONCLUSION

This paper presents a comperehensive algorithm for passive defans of enclosure with aperture with probability of confrontation of EMI. This algorithm includes structural method of field distribution simulation via MOM for SE computation in the desired frequency range, secure route optimization using AHP method as hardware point of view and TC and MAC algorithm as secondary software protection. We introduced an advanced security algorithm for solving EMI problems and data transmission errors. In this method, firstly, the shielding computation is performed to achieve the desired SE factor and the control room is extremely protected against electromagnetic interference. Then, in order to achieve better security conditions, Optimization of the data transmission path is performed by AHP Method the best route is selected

based on the indexes. Finally, to improve the results, coding has been used to increase security and reduce BER. In the proposed method, the BCJR algorithm is used. Despite the complexity of this algorithm, as is evident in simulation results; BER is greatly reduced compared to previous methods (Viterbi decoder). This decrease from 10^{-1} to 10^{-2} in the results is clear.This method could be used as a hybrid solution for increase the security issues and can be generalized to all modern industrial systems, control and monitoring equipment.

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