

Quantification of Complexity and Coupling Indices to Validate Normal Accident Theory in Telecommunication  
Network Accidents

Madeline Martinez - Pabón, M. Eng; EMC Corporation; Franklin, Massachusetts, USA

Charles Kim, PhD; Howard University; Washington, DC, USA

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Abstract

A system or organizational perspective has gained its importance in explaining rare and high impact accidents because it helps us to understand the complex nature of highly technical systems and the accident causes. Safety is a critical issue in telecommunication networks; therefore, understanding the inherent characteristics of the network in relation with accident occurrence has considerable merit for safer design and operation of a telecommunication network. This work of investigating a telecommunication network and its accidents applies an organizational accident theory, Normal Accident Theory (NAT), and determines if the telecommunication network belongs to a highly technical system in which accidents is 'normal' and 'system inherent.' NAT links the occurrence of unplanned and untoward events or accidents to interactive complexity and tightly coupled systems, but without quantifiable measures of the terms of 'complexity' and 'coupling'. In this work, the complexity is calculated by measuring potential system states while the coupling is quantified by measuring two attributes, redundancy and time dependency. By applying the three defined quantities on a real telecommunication network and its actual accident history and by comparing them with those of other systems, this research places the telecommunication network as a complex and tightly coupled system.

Introduction

Organization plays an important role when determining the root causes of accidents and must be investigated in order to prevent future accidents. There are two schools of thought that have studied organizational causes of accidents: Normal Accident Theory (NAT) (Ref. 1-2) and High Reliability Organizations (HRO) (Ref. 3-4). The initial formulation of NAT was made by Charles Perrow after the accident at the Three Mile Island Nuclear Power Plant that occurred in 1979 (Ref. 5). He stated "The term normal accident is meant to signal that, given the system characteristic, multiple and unexpected interactions of failures are inevitable" (Ref. 1). Moreover, he explains that accidents will be inevitable when the system has an interactive complexity and is tightly coupled. Complexity will cause a system to have unexpected interactions and this causes the system to face a higher probability of having accidents. When a system experiences the presence of unexpected events, and they are not visible easily then the system can experience an interactive complexity. High interdependent systems refers to the tightly coupled characteristic of NAT: The system is formed by subsystems, units or parts, and when these elements are interconnected together in a tightly way then the response of a system to a specific event can propagate to the other part that are linked together, affecting the current status of the parts. The numbers of links in a loosely coupled system are fewer; therefore, if there is a failure in a specific part of the system, it does not propagate rapidly. It means the unplanned or unexpected event can be fixed before it affects other parts of the system, avoiding the destabilization of the whole system. Perrow has concluded that "Accidents are inevitable and happen all of the time; serious ones are inevitable but infrequent; catastrophes are inevitable but extremely rare" (Ref. 6). Coupling and complexity can be predictors of the expectation of failures in telecommunication networks according to NAT. NAT occurs in systems with many components, complex interconnections, strict dependencies and stringent performance conditions. In systems like this, it will be impossible to predict all the failures, accidents or incidents foresee that might happen. Between design limitations, equipment failures, procedural errors, operator error, problems in supplies and materials, and unknown variables in the environment, there will always be unforeseen complications and unexpected contingencies.

On the other hand, the HRO school of thought sees NAT as “pessimistic” (Ref. 2). It asserts that we can achieve reliability with appropriate organizing. Therefore, we have two opposed schools, Normal Accident Theory and High Reliability Organizations each positing conflicting views of the organizational factor of accidents in systems. The research that has been made to validate these schools of thought is little. However, an important study made during the cold war by U.S. Air Force committee concluded that Normal Accident Theory provides a better understanding when explaining the safety of nuclear weapons (Ref. 2). The contribution that Perrow made in identifying these two parameters that shows the increasing risk of accidents in a system was very important and the first step to continue the study of this two characteristics not only in petrochemical plants but in other fields such communications. One of the suggestions that HRO does about increasing safety in systems is adding redundancy to it; however, Perrow contradicts this idea arguing that adding redundancy or more elements to the system will increase the possibility of having more accidents because the system’s complexity will be higher. However, he also agrees that the only way to improve safety in systems is adding redundancy to it. Therefore, adding or not adding redundancy to the system will not stop an accident to occur (Ref. 7).

### Applicability of NAT to the Telecommunication Network Located in Valledupar, Colombia

The telecommunication network that is analyzed in this research work is located in Valledupar city, Colombia. The Telecommunication network is shown in Figure 1.

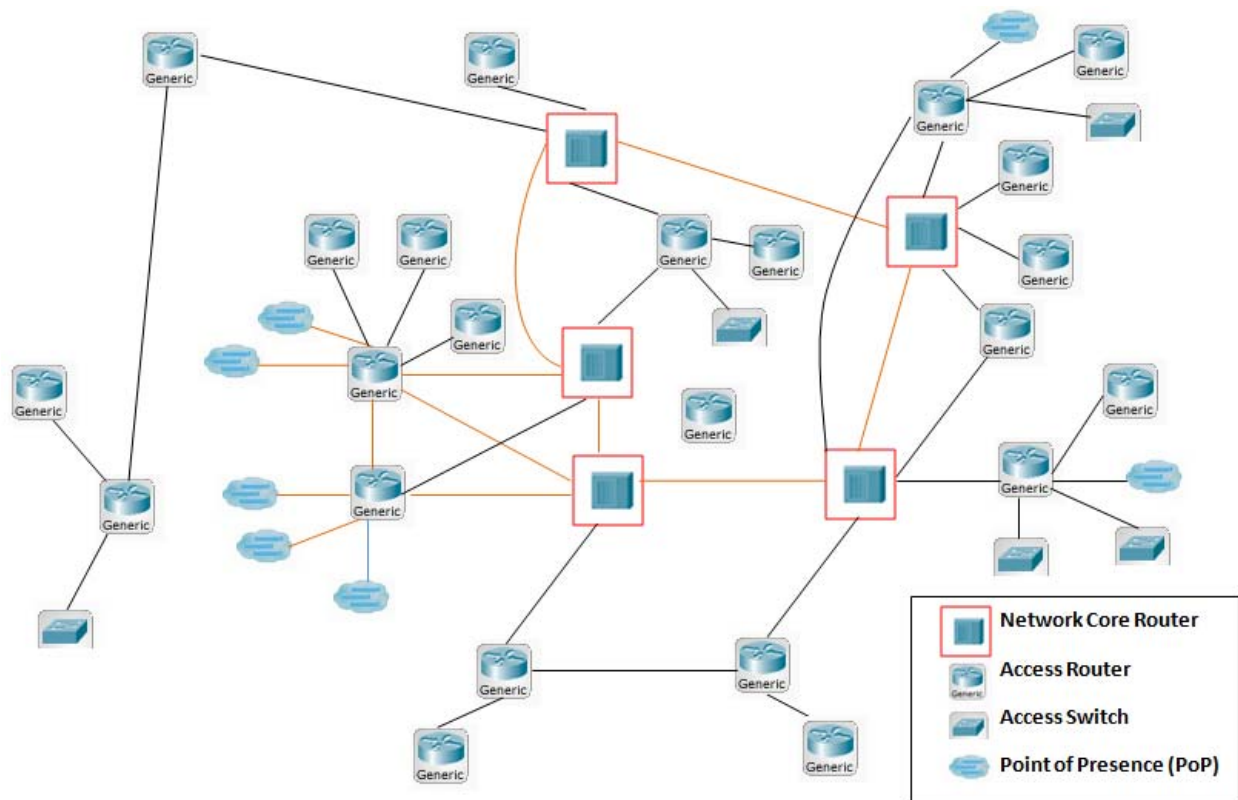


Figure 1— Section of Telecommunication Network in Valledupar, Colombia

The portion of the telecommunication network of Valledupar city consists of six main elements: network core routers, access routers, access switches, regular routers, Points of Presence (PoP) and of course the Internet Access. The network has 54 nodes; each of them plays an important role in the study of the network.

Differentiation between Normal Accidents and Component Failure Accidents in Telecommunication Networks: NAT distinguishes two kinds of accidents, those are: system accidents and component failure accidents. System accidents are caused by the interaction of the components that form a system. Therefore the components of a system experience an interactive complexity. Even though the equipment is working properly the combinations of elements caused an accident. We can conclude by now that NAT accidents are system accidents; therefore, the fatal combination of interactive complexity and tight coupling may cause an accident. If the components of a system become tighter, then it becomes more difficult to predict the interaction between the components. As system components grow more tightly coupled, it becomes more difficult to foresee the interactions the components have (Ref 8). Systems accidents are also called Normal Accidents, and the Three Mile Island (TMI) accident is a typical example of these kinds of accidents. On the other hand, component failure accident can be the result of one or more failures in subsystems or units inside the system. Most of the accidents in the telecommunication industry seem to be part of component failure accidents. However, this paper determines if normal accidents can be possible in telecommunication networks.

Classification of Accidents in the Telecommunication Network in Valledupar, Colombia: The accident report of the telecommunication network that is shown in figure 1, states that there were approximately 42 accidents or incidents. The classification was made based on Perrow's classification of accidents. First we have to state that according to Perrow systems are divided in four levels of increasing aggregation: units, parts, subsystems and systems. Based on this increasing aggregation, we can give an appropriate definition of what we are calling an accident, and then classify them in the proper kind of accident. Perrow defines two kinds of accidents: Component Failure Accident (CFA) and System Accidents (SA). Component failure accidents "Involve one or more component failures (Part, unit or subsystem) that are link in an anticipated sequence" (Ref. 1). On the other hand, system accidents "Involve the anticipated interaction of multiple failures" (Ref. 1). In other words, the difference between component failure accidents and system accidents is on the basis of whether any interaction of two or more failures has occurred. Our classification of accidents is consistent with Perrow's classification and some example of component failure accidents of the network we are analyzing are: Improper configuration of routers and switches, subnet mask Settings are incorrect, duplicate IP address in the router, transformer failure due to deterioration, etc. In total there are 42 component failure accidents according with our classification. On the other hand, we found only a system or normal accident that was caused by the interaction of several failures in a consecutive way: This is the list of source causes and the final result.

1. Wind damaged access router
2. Operator was unable to fix the router because of lack of training and inexperience.
3. Congestion in the router inband path.
4. Memory allocation failure in the router
5. Traffic disruption

The telecommunication network report consists of 43 accidents. They were classified as component failure accidents or system accidents. We found that there is just one system accident in the report. This accident was the result of a concatenation of events that resulted in the inoperability of that session of the network.

#### Operationalization of Complexity in Telecommunication Networks To Validate Normal Accident Theory (NAT)

To measure a system's complexity we must look at the interactions between the components of the system. Most systems are designed with linear interactions in mind. Linear interactions are sequential interactions where a component will typically get its input from an "upstream" component, do some sort of transformation, and subsequently deliver its output to a "downstream" component. If one component fails, it is relatively easy to locate and understand the point of failure and consequently handle it without catastrophic results. On the other hand, if a component of the system serves multiple functions or is connected to several other components, the interactions are said to be complex.

Analysis of Complexity Index Used to Validate NAT In Telecommunication Networks: Interactive complexity may be understood as the number of potential system states. Complexity will be operationalized as a Complexity Index computed by measuring potential systems states using the complexity index defined by Wolf, F.G. Wolf researched the validity and application of NAT to petroleum refineries by defining a refinery system as a hierarchy of system units, links, and nodes. In the same way, I will define a telecommunication network as a hierarchy of system units, links and nodes. For each node, critical parameters can be defined which describe the process system's behavior at that specific location. The complexity index is calculated using equation 1:

$$C = \prod_i C_i = \prod_{i=1}^n \left( \prod_{j=1}^m (Q_{ij}) \right) \quad (1)$$

Where:

- $C_x$  = Complexity of a specific telecommunication network
- $n$  = Number of nodes in a specific telecommunication network
- $m$  = Number of parameters at node i
- $Q_{ij}$  = Number of possible states of parameter j at node i
- $Q_i$  = Number of possible states of all parameters at node i
- $C_i$  = Number of possible states of all parameters of all nodes for the network

The complexity of a telecommunication network is expressed in the number of NODES, which are points of connection and interconnection between processes and their linkages. Obviously a more complex system will consist of more nodes than a less complex system, but nodes do not provide adequate insight into complexity for a valid test of Normal Accident Theory which deals with interactive complexity. This information provides a basis for operationalizing the two variables proposed by Perrow, complexity and coupling. For each node, critical parameters can be defined which describe the system's behavior at that specific location. The finite set of parameter states defines the operational envelope of the system and provides the basis for a useful index of refinery-specific complexity which can be calculated by the equation. The complexity index that we chose in this research was already validated by Wolf (Ref 9) in petrochemical plants. We used the same method he used validated NAT, and in our case applied to telecommunication networks. This research made a comparison between the two systems, telecommunication networks and petroleum refineries that show that the equation can also be used in our research. According to the complexity index used every node contains parameters that describe the way the subsystem or unit work. The number of parameters to be assign to a node can be infinite; however, for calculation purposes it was recommended to use those parameters that are relevant for a specific function of the node inside a system or organization. Furthermore, the only way to describe the activity of a unit through a parameter is introducing the concept of "states" for every parameter. States are qualitative definitions to give information about the current status of the system in a specific subsystem or component.

In our case, the telecommunication network at Valledupar city has 6 possible nodes. Every node is characterized by parameters, and every parameter is quantitative measured using states. For example, our node 1 has 5 different parameters: power consumption, flash memory, rack-mounting, noise level and DRAM. Every parameter has possible states; for example, power consumption has three different possible states: high, normal or low. After analyzing all the states in every parameter in all the 54 nodes in the network of Valledupar the complexity index was calculated using equation 1, and the result was the value:  $C_x=108.78$ . This number will be used in further sections to make conclusion about the application of NAT in telecommunication networks.

### Operationalization Of Coupling In Normal Accident Theory

The concept of coupling is used by Perrow to classify systems according to the strength of the connections between their internal components. The term tight coupling is meant to describe a situation where there is no slack or buffer between two items, so that what happens in one directly affects what happens in the other. Continuous processes "are more tightly coupled because they are generally invariant, time dependent, highly sequential, and have little

slack. Semi-continuous and batch processes are more flexible in terms of timing and sequencing so they are classified as less tightly coupled or loosely coupled systems”. (Ref 10)

Loosely coupled systems processing delays are possible, the order of sequences can be changed, alternative methods to achieve the goal are possible, and slack in resources is possible. It is important to emphasize that a system is not either complex or linear, nor is it either tightly or loosely coupled. Any system will have both complex and linear interactions and tightly coupled as well as loosely coupled subsystems. Perrow’s point is that the more complex interactions a system exhibits, and the more tightly coupled it is, the more the risk of accidents increases, and so the vulnerability of the system (Ref 11). In general, the attributes in a tight coupled network are shown in Table 1. This research uses the first two attributes in a tightly coupled network to validate NAT. These attributes are: Time dependency and Flexibility.

Table 1 — An Attributes in a Tightly Coupled Network

Tight Coupling attributes	Comments
Flexibility	Less tolerant of delays
Time - Dependency	The system is less redundant
Sequences	Invariant sequences
Slack	The structure has little or no slack
Substitutions	The components, units, or subsystems cannot be substitute.

Analysis of redundancy as our first parameter to calculate coupling: Flexibility in a telecommunication network can be determined by calculating the degree of redundancy in the network. We can do this, calculating an index called “Vertex degree magnitude-based information content  $I_{vd}$ ”, mathematically described by equation 2. Where  $I_{vd}$  is the Vertex degree magnitude-based information content, and  $a_i$  is the Vertex Degree.

$$I_{vd} = \sum_{i=1}^v a_i \log_2 a_i \quad (2)$$

This equation was derived from Shannon’s Theory which has been widely used in chemistry as an Information index. Shannon’s information was chosen to calculate redundancy in the telecommunication network because it gives us information about the topology and interconnection of our system. It means that it is perfect to determine, if a system is redundant or not. This theory was amply used in the past to determine complexity; however, in our case it does not gives us information about the functionality of every component in the system. It makes it an improper element in the calculation of complexity, but perfect for the calculation of our redundancy index. This index increases with the connectivity and the number of branches, cycles, cliques, etc. The increase in the number of branches increases the Vertex degree magnitude-based information content  $I_{vd}$ . If  $I_{vd}$  increases the telecommunication network becomes less coupled. Its value in the telecommunication network of Valledupar is  $I_{vd} = 75,58$ . The Redundancy index is defined as  $R_x = 1 / I_{vd} = 0.0132$ .

The implications of this number in our research will be discussed in a further section, when we will put all the elements together to analyze the applicability of NAT into telecommunication networks. Time-dependence is the second attribute that we will consider in this research to calculate coupling in telecommunication networks. Time-dependence is linked with delay in the system. To calculate the delay in the system we are using a powerful graphical tool called “Petri-Nets”.

### Using Petri-Nets To Calculate The Delay In A Telecommunication Network

Petri-Net is a powerful tool that facilitate us the use of time in the analysis of system's performance. The general structure of Petri-Nets systems is composed of a set of places, a set of transitions, markings and tokens. Also, it is constituted by an input function (Input arcs) and an output function (Output arcs). The graph structure usually illustrate a place as a circle "O", and bar "|" as a transition. An arrow from a place to a transition is represented as an input to the transition. While an arrow from a transition to a place represents an output place. The dynamic attribute of Petri-Nets is defined by tokens to places in a Petri-Net. The tokens are denoted by Markings which may change during the execution of a Petri-Net. The execution and performance of a Petri-Net is controlled by the distribution and number of tokens in the Petri-Net. The condition for a transition to fire is that every place that is linked to a transition contains the necessary number of tokens. Once this condition is fulfilled, then the transition will fire, sending the token or tokens to the correspondence places. The tool used in our research to model our telecommunication network is called: Colored Petri Net (CPN) tools (Ref 12). CPN tools help system designers to model and validate systems. A CPN model represents states of a system and events that force or cause a system to change from a state to another. CPN tool is the computer tool used to simulate the telecommunication network located in Valledupar, Colombia.

Petri Net Model of a Telecommunication Network: The telecommunication network model is formed by three main parts: The TCP/IP level and the transmission and receiver level. The Colored Petri Net (CPN) model follows the Petri Net concepts studied in previews sessions. Figure 5.9 shows the three parts that form de total system. These parts are: The TCP/IP level, the transmission system and the receiver level. The model is formed by 14 places, 9 transitions and several arcs, and each session can work independently. Figure 2 shows a Colored Petri Net with the TCP/IP model.

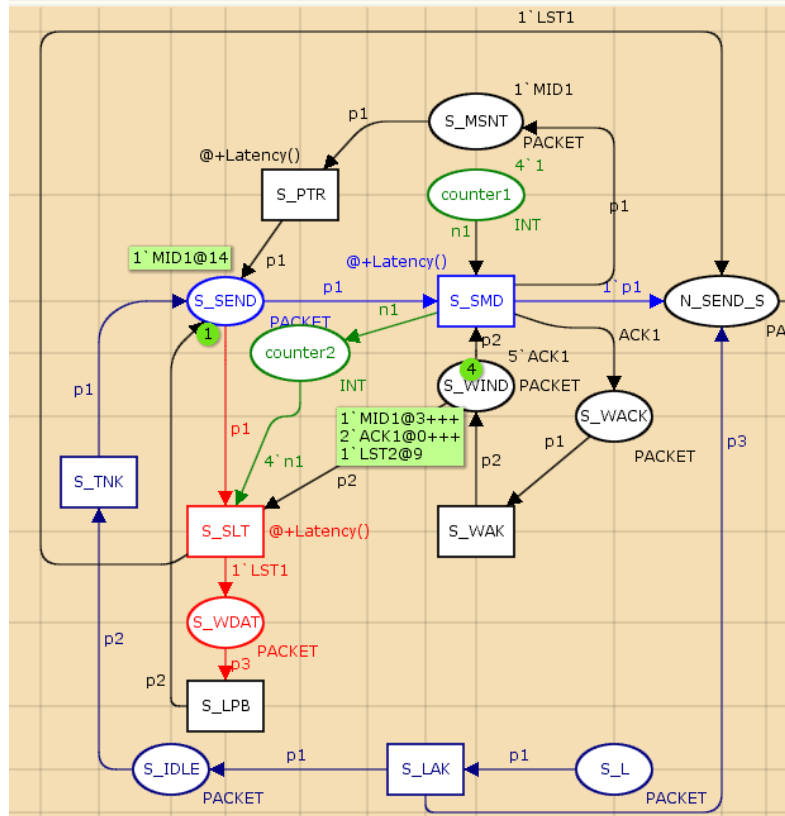


Figure 2 — TCP/IP Model

In the model, three colors are used for the three packet types: MID1, LST1 and ACK1. The control token cycling through places S\_IDLE, S\_SEND and S\_WDAT represent user/application. When the control token is in place

S\_SEND, both transitions S\_SMD and S\_SLT are enabled. This structure is simulated using two counters (Counter1 and Counter2). In our simulation we have a packet that has five elements, four of them are regular packets (MID1) while the last one represents last element of the packet. Counter1 allows the flow of four “regular packets” through the system and after the fourth packet is sent, the fifth (LST1) element is sent when counter2 give the order. If no tokens are present in S\_WIND, the number of unacknowledged packets is at maximum. Tokens are also deposited in places S\_WACK. The firing of transition S\_PTR returns a token to place S\_SEND (after a delay representing the time needed for assembling a new packet of data). This cycle continues sending MID1 elements of the packet until S\_SLT fires and sends a LST1 which indicates the end of data group. The delays in the system are represented by a discrete function called “Latency”. This discrete function can be any number between 1 and 2 microseconds. This time represent the delay when the TCP/IP model organizes the packet and get everything ready to transmit the packet. In our system there are three transitions that have delays, and they are: S\_PTR, S\_SMD and S\_SLT.

Figure 3 shows the model of the transmission system and the receiver. This is a simplified model that simulates the total delay in the system through the discrete function called ‘Delay’.

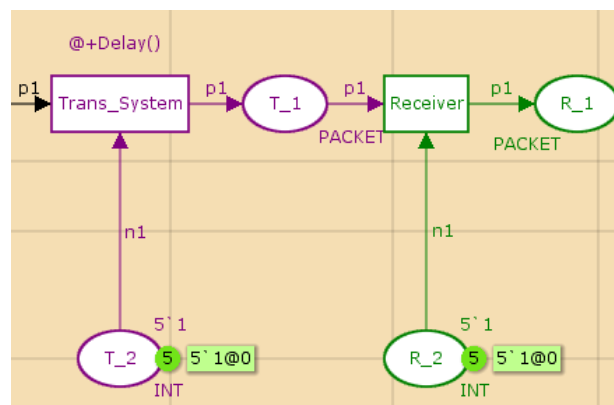


Figure 3 — Transmission system and Receiver level

This discrete function can be any value from 60 to 105 milliseconds. These boundaries were chosen based on the fact that a delay between 60 ms and 110 ms is considered as acceptable. (Ref 13) Delays with greater values in the network are considered as unacceptable because can lead to lost or distorted packets.

**Model Performance:** The CPN model of our system describes how the packages in the telecommunication system change from one state to another one through a series of events (transitions). With the simulation of the model, we can explore the behavior of the system by running different scenarios. The main purpose of simulating our network using CPN tools is to test the system and do performance analysis. In telecommunication networks, time plays an important role because of concurrency in the system. Visualization is one of the advantages of using this tool because allow us to see the animation of the system and how tokens move from one place to another while a transition is activated. In order to calculate the delay in the system, our telecommunication model using Colored Petri Nets was ran 100 times. Every time we run our system we focused on the value of the LST1 element inside the packet which represents the last element of the packet. Unacceptable delays are those beyond 110 milliseconds. In our simulations we have 13 values in the range between 111 - 120 milliseconds, and 2 delays in the range of 121 – 130 milliseconds. In total we have 15 delays out of the acceptable range. The analysis of this finding are discussed in the next section where all the results are placed together to finally conclude if our system is complex or not.

### Analysis of Results

In this section we place the complexity and coupling index in a Complexity vs. coupling graph. Then, we will compare these values with some systems that according to Perrow (Ref 10) are part of NAT such as: chemical Plants, space missions, nuclear plants, military early warning and aircrafts. We use some results that Wolf obtained in his paper [12] where he calculated the complexity index of petroleum refineries to establish very important points

in our complexity vs. coupling graph. In Figure 4 we divided the graph in four sections or quadrants. The x axis represents complexity while the y axis represent coupling. The first quadrant contains systems which are simple and tightly coupled. The second quadrant contains systems that have interactive complexity and tightly coupled. Third quadrant is for simple systems and loosely coupled, and finally the fourth quadrant is reserved for system with interactive complexity and loosely coupled. Firstly, the complexity index in petroleum refineries is  $C_x=30$ . Our complexity index is  $C_x=108.75$ . It means this value must be in the right side of the graph, as seen in Figure 4, and we can conclude that our system has interactive complexity.

After the calculation of our redundancy index using the Vertex degree magnitude-based information content  $I_{vd}$ , we obtained the value:  $R_x=0.0132$ . However, it can be placed in the upper or lower side of the graph. To decide the correct placement of our redundancy index, we have analyzed the delay in the telecommunication network using a powerful graphical tool called “Colored Petri Nets (CPN)”. After running the simulation of the telecommunication network 100 times, we see that 15 times the simulation was place above the acceptable range (110 ms). It means that 15% of the packets will be lost according to the results. These results contribute to determine that telecommunication networks are very sensitive to time delays; therefore it is concluded that it is a tightly coupled system. Therefore our telecommunication network is finally placed in quadrant 2 of the complexity vs. coupling graph, and the results can be seen in Figure 4.

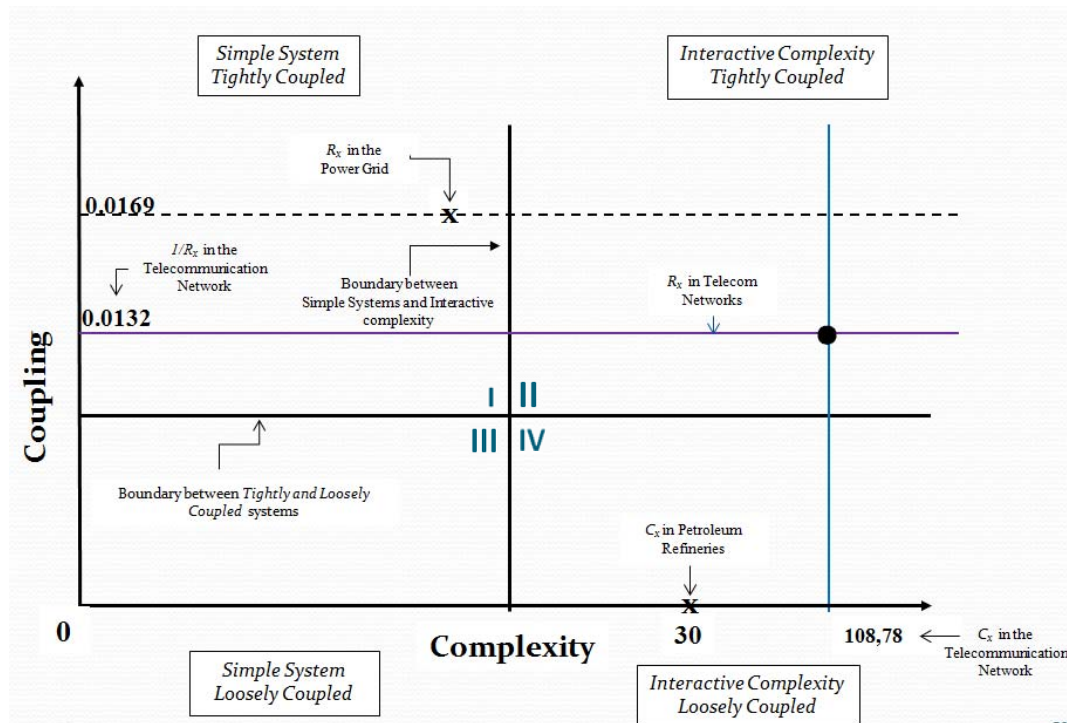


Figure 4 — Placement of the telecommunication network system in the second quadrant (Systems with Normal Accidents)

### Conclusion

The accident events and failures in telecommunication networks, the causes of some of them remained unresolved, and the high impact of the accidents made in the society inspire to investigate the inherent characteristics of telecommunication networks in relation with accident occurrence. This research work attempts to answer the question if a telecommunication network is too complex to keep it safe and reliable regardless of the efforts to keep highly reliable. In other words, the research tries to determine if telecommunication networks are, in terms of the



normal accident theory, complex and tightly-coupled organizations so that the accidents in them are normal, natural, and system-inherent. In the investigation, the qualitative measures of the terms, complexity and coupling, are quantified and the quantified terms are used in determining the placement of the telecommunication networks on the interaction-coupling chart of the normal accident theory. For complexity, an index of structural characteristics, which has been applied in analyzing petrochemical refineries, is adopted and, after the analogical analysis of the telecommunication network's topology and degree of interconnection, applied in calculation of the complexity index. For coupling, two attributes are selected, flexibility (or redundancy) and time-dependency, and for the former the concept of information content is applied in calculating the redundancy of the network while, for the latter, the rate of lost message in different delay times is statistically measured. When a system is more redundant, the system becomes less coupled; however, when the system is less redundant then it becomes tightly coupled. Also, when a system is more sensitive to time and time delay, the system is said to be tightly coupled. The three indexes described above are applied to a real telecommunication network located in Valledupar, Colombia, and compared with those of petrochemical plant and power grid, which are classified as interactively complex and tightly coupled systems and placed thereupon in the second quadrant on the interaction-coupling chart, to find the placement of the telecommunication network relative to them in the chart. It is found that the telecommunication network is more complex than petrochemical refineries. For coupling, in redundancy measure, it is found that the telecommunication network is less coupled than power grid. On the other hands, the time dependency analysis, performed with Petri net simulation of statistical time delay and missed message rate, finds that about 15% of message is lost if a time delay is above a certain level, and hence leads to conclude that the telecommunication network is time-sensitive and thus tightly coupled. Therefore, the telecommunication network is placed in the same quadrant on the chart as the petroleum refineries, the second quadrant, in which nuclear weapons systems and nuclear power plants are also placed. In conclusion, it can be said that a telecommunication network is a complex and tightly-coupled technological system and, following the normal accident theory, is too complex to keep it safe and reliable regardless of the efforts to keep it highly reliable, and that the accidental events and failures in telecommunication network are normal, natural, and system-inherent. A possible mode of such normal accidents is an unexpected interaction of components, cascaded into a series of unanticipated events, which eventually leads to serious and high impact consequences.

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### Biography

Madeline Martinez, M. Eng, Test Engineer, EMC Corporation, 55 Constitution Boulevard Franklin, MA 02038, USA, telephone – (240)370-5430 – e-mail – [madeline\\_8303@hotmail.com](mailto:madeline_8303@hotmail.com)

Ms. Madeline Martinez received her BS in Electronic Engineering (2007) from Industrial University of Santander (Bucaramanga, Colombia) and recently received her Master in Electrical Engineering (2012) at Howard University. She has worked on several areas such as Telecommunications and Power Systems. Madeline's research interest includes safety analysis of Telecommunication Networks and sustainable energy systems. Currently, she is working for EMC Corporation as a test engineer.

Charles Kim, PhD., Associate Professor, Department of Electrical & Computer Engineering, Howard University, 2400 Sixth St, NW Washington, DC, 20059, telephone – (202) 806-4821– e-mail – [ckim@howard.edu](mailto:ckim@howard.edu)

Dr. Charles Kim received a Ph.D. degree in electrical engineering from Texas A&M University (College Station, TX) in 1989. Since, 1999, he has been with the Department of Electrical and Computer Engineering at Howard University. Previously, Dr. Kim held teaching and research positions at Texas A&M University and the University of Suwon. Dr. Kim's research interests include failure detection, anticipation, and prevention in safety critical electrical/electronic systems in energy, aerospace, and nuclear fields.