Modeling Technological Interdependency in IoT – A Multidimensional and Multilayer Network Model for Smart Environments

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***Abstract*—The Internet of Things (IoT) has changed the shape of edge networks by adding various technologies to support a wide range of services from interactive and high-bit-rate to battery-operated, long-range and low-bit-rate services. While the diversity of heterogeneous technologies can be exploited to increase network resilience, a proper model is required to understand, design, and analyse the relationship between these technologies and the overall smart environment. In this paper, we propose a formal multidimensional multilayer model to describe the Internet and IoT topology from functional, geographic, and technology-level perspectives. This model is intended to capture the complexity of the smart-home and smart-city environments attached to the Internet through diverse access technologies including emerging 5G mobile networks. We analyse the resilience of diverse network technologies for smart homes using our technology interdependence graph.**

I. INTRODUCTION

Multilayer networks serve as an extension of standard graph modeling techniques. They allow the representation of complex systems with multiple types of interconnection. This is especially valuable when we consider changing network properties given the integration of distinct kinds of networks. For instance, a simple network with highly connected nodes is more robust in the face of a link failure than a network with sparse connectivity. However, the same characteristic makes interconnected networks more vulnerable to a cascade failure from one network to another [1].

Using multilayer graphs to represent the Internet as a complex network is not new. One way of representing the Internet topology is by describing it as functional levels containing physical, router, point of presence (PoP), and autonomous system (AS) levels [2], [3]. In previous studies, functional levels have been represented as multilevel graphs with different degrees of detail including multilevel, single provider [4], [5], [6] and multilevel, multi provider [3] structures. However, the so-called Internet of Things (IoT) has expanded the edge networks rapidly and added more complexity to the overall structure of the Internet. New models of network connectivity are required in order to help us capture the details associated with this added complexity.

In this paper, we propose a multidimensional, multilayer network to illustrate how characteristics of network connectivity at different layers of the Internet are changed by the addition of IoT. Here, we focus on the smart home environment as one of the components of the IoT ecosystem in which various smart environment including transportation and energy are involved. Although the focus of this paper is modeling smart homes, any edge network can be represented by our multidimensional model.

The paper is organized as follow: We begin by introducing our multidimensional model for smart environments and present our smart home model in Section II. We show how this model allows us to study those aspects of IoT that have implications for network resilience. Specifically, we use our *technology interdependence graph* and *multidimensional model* in Section III to propose a new degree centrality metric to more adequately represent the effects of multiple interdependent technologies on complex networks. Finally, we conclude our paper in Section IV.

II. SMART HOME MODEL

The multilayer networks frameworks can represent distinct kinds of temporal and spatial relationships more fruitfully than a single-layer network [7]. As we show elsewhere, smart homes and smart cities can be helpfully characterized by a multilayer approach [8] since these systems are a network of interacting networks from various technologies. Furthermore, smart homes are part of smart cities and these, in turn are part of the Internet which is itself a complex network. Thus, formal representations of the behavior of the Internet as a whole is suited to multilayer network modeling.

Before we define our multidimensional framework, we explain the following network-related terminology.

A. Terminology

- *Monoplex network*: A single-layer network.

- *Multiplex network*: A multilayer network with inter-layer edges only between representations of the same node in different layer (diagonal coupling) [9].
- *Interconnected network*: A multilayer network with inter-layer edges between any two nodes [10].
- *Interdependent networks*: Two or more monoplex networks connected via edges called *dependency edges* [9]. Dependency edges are one of the reasons to facilitate cascade failures and should be treated differently than the intra-layer edges in monoplex networks.
- *Multilevel network*: A multiplex network with a particular order of layers [11].

Obviously, no graph-theoretic representation can illustrate all the attributes and behaviors of real-world systems. We must be selective. However, in the context of IoT, the role of technological interdependency becomes important enough that our formal representations should capture it. As we will show, by including interdependency, the multilayer approach permits the formal study of network properties that are hidden in a single-layer approach. In particular, multilayer networks highlight *dependency edges*, as defined above. Furthermore, multilayer network representations can be transformed into multidimensional representations when different *aspects* of a network are involved, as will be explained below. Consequently, by modeling relevant interdependecies among network layers systematic features may be revealed. Interdependencies can include *physical interdependency* when material or energy exchanges between networks, *cyber interdependency* when information flows between networks, and *geographical interdependency* when spatial proximity is important [12]. These distinct relations of interdependency may be modeled depending on what is most relevant for the researcher. For instance, physical interdependency is involved when a power grid network is integrated with a communication system. A multilayer graph model can be an appropriate tool for representing the behavior of communication systems that have interdependent relations with other systems.

B. Smart home multidimensional model

Before formally introducing our multidimensional framework, we provide an instance of a complex smart home network. With the formalism in place we will then show how to apply our multidimensional approach to this network.

The smart home multidimensional model is illustrated in Figure 1. In this model, the horizontal axis (x-axis) represents the network depth including core, access, and edge networks. The vertical axis (y-axis) shows the network levels while z-axis illustrates the technology variants.

Consider the network representation offered in Figure 1. Here, the Internet is treated as a complex network with various functional *network levels* supervening on the lower levels [13]. The figure shows the *physical infrastructure* containing physical network connectivity, a logical *network layer* to provide logical path from a source to a destination, autonomous systems (AS) level organizing routing elements under control of autonomous entities, and *end-to-end (E2E) topology* level that represents an end-to-end connection between a source and a destination. Notice that, in this representation, the number of nodes and edges decreases from lower layers to higher layers. More precisely, in this representation the nodes in a particular layer are a subset of those in its lower layer.

Furthermore, in this representation the Internet is divided into *core*, *access*, and *edge networks*. The Internet core contains all tier 1 ISPs in different functional levels to establish internet connectivity. Tier 3 ISPs usually provide internet connectivity to end users through access networks such as hybrid fiber/cable (HFC) and DSL. The *depth* of the network should be understood as the distance from the Internet core to the edge of the network. The physical infrastructure of the access networks along with the routing levels is connected to the corresponding levels of the Internet core.

Currently, one rapidly growing part of the Internet is the edge networks composed of the end-user networks such as home, city, enterprise and industrial networks connected to the access networks. Regarding the addressing and forwarding methods, the routing level of the edge networks may not connect to the Internet core directly. Network address translation (NAT) and non-IP routing protocol such as ZigBee are two examples requiring a gateway to connected the network layer of an edge network to the corresponding access layer indirectly.

We observe especially high levels of diversity at the edge networks due to the highly diverse requirements of different services. While the main type of service in the Internet core is relatively error-free, high-bandwidth connectivity with low delay, required service types at the edge networks vary from very-low to high-bit-rate connectivity with different level of energy consumption. Variability with respect to range of service also affects the routing level to provide the routing services with a lower energy consumption and a shorter packet size.

C. Formal definition of the model

Given the growing significance of IoT to the architecture of the Internet what is needed is a formal framework to represent properties of network topology for different technologies at the edge networks. We define a multidimensional network that captures disparate network *aspects*, $\mathfrak{G} = (\mathcal{G}, V_N, E_N, V, S, N, A)$. Each aspect represents a feature of the network such as functionality, geographic distribution, and technology variants with an associated set of values for each aspect illustrated in Figure 1. In other words, each aspect is equivalent to a feature that can be represented as one dimension of a multidimensional network. Increasing the number of aspects is possible depending on the interests of the researcher. Here, we use three relevant aspects in our discussion for simple graphical presentation. Figure 2 shows the abstract form of the graph $\mathfrak{G}$ with three aspects X, Y, and Z. Each plane in the Figure represents one *slice*. In other words, one slice in a three-dimensional model is a plane containing all values for two aspects. The intersection of d slices, where d is the number of aspects, represents a *net*. Each

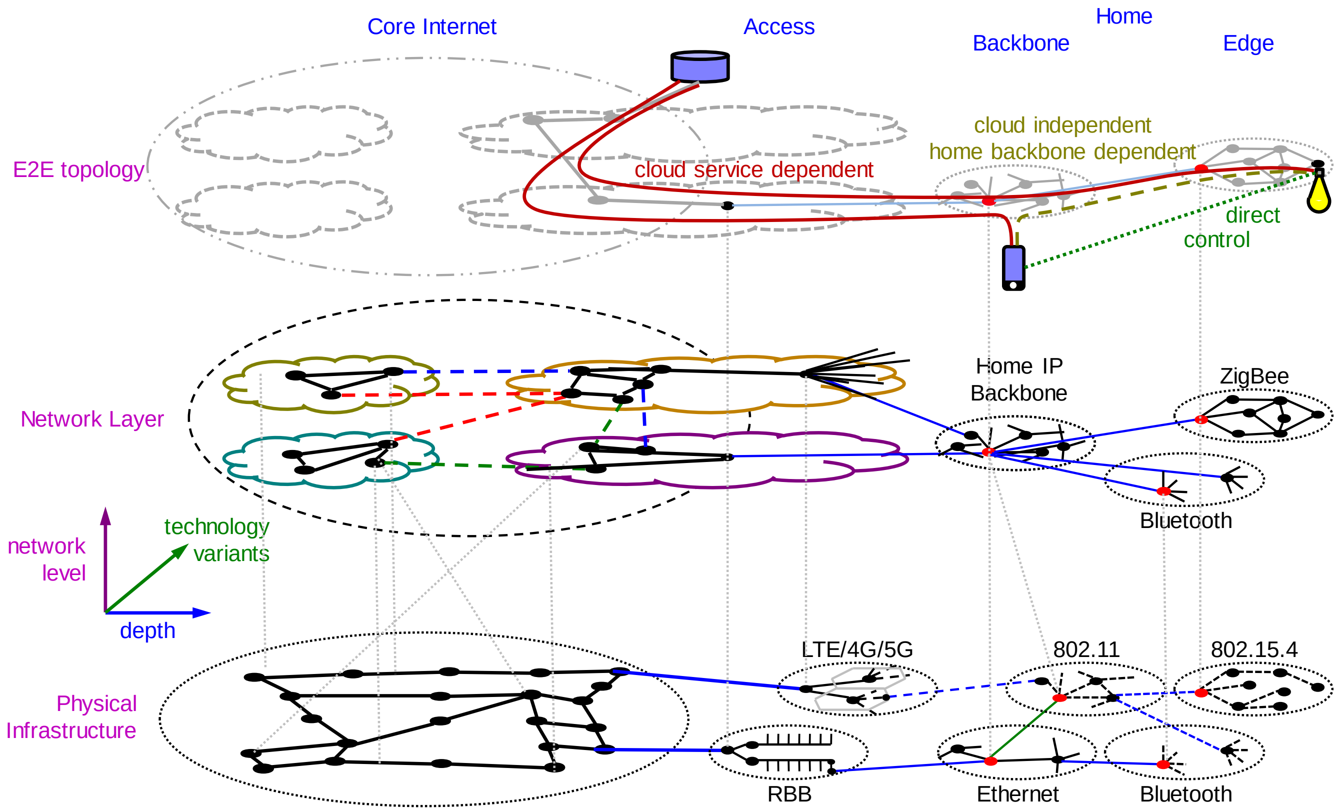

Fig. 1. Smart home multidimensional model

net shows part of the overall graph with some specific value for each aspect. For example, in Figure 1, a net can represent the physical infrastructure of a home backbone implemented with 802.3 technology while a slice can show the whole physical infrastructure of the network with all technologies in the network depth. As another example, a net can be the physical infrastructure of the LTE technology employed in the access layer while the corresponding vertical slice containing the LTE physical infrastructure represents the network level aspect of various technologies in the access layer.

We can modify the level of network abstraction by changing the number of values of a particular aspect. For example, we can combine the home backbone and the home edge in Figure 1 to one aspect value as *home* to consider all employed technologies in a smart home together as presented in Figure 3. Note that we use axes in Figure 2 for clarity of presentation; however, the axes do not have any algebraic value since the aspects have nominal values. Moreover, we can show the network aspects more intuitively on these axes.

We summarize our model terminology as follow:

- network *aspects* are a set of features represented by a multidimensional network.
- *values of an aspect* are a set of values for each aspect.
- *rules of an aspect* are a set of rules on values of each aspect such as the order of values.
- one *slice* is an area in a d-dimensional network representing a graph with a set of nodes and corresponding edges that have $d-1$ aspects in common.
- a *net* is the intersection of d slices in a d-dimensional network. A net represents a graph with a set of nodes and corresponding edges with specific values for all of the aspects in the network

We define our multilevel graph framework as $\mathfrak{G} = (\mathcal{G}, V_N, E_N, V, S, N, A)$ with the following conditions:

1) A is a set of aspects where $A = \{a_0, a_2, ..., a_{d-1}\}$ and d is the number of aspects in the network.
2) For each aspect $a_i \in A$, a_i has a rule and a set of values where $a_i = \{a_{i_0}, a_{i_2}, ..., a_{i_{q-1}}\}$ and q is the number of values in aspect a_i and $q \geq 0$. If $q = 0$ then the corresponding aspect is eliminated. Furthermore, $\mid a_i \mid$

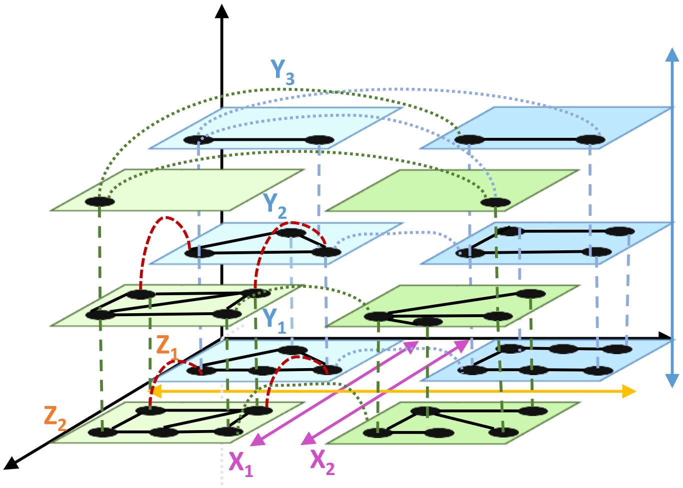

Fig. 2. General representation of the multidimensional model

represents the number of values for aspect a_i. The rule r_i for each a_i denotes a set of constraints on a_i such as the order of values.

3) N is a set of nets where $N = \{n_0, ..., n_{p-1}\}$.
4) for every net $n_l \in N$, n_l represent a graph G_{n_l} for each value of the Cartesian product $l \in \{a_{0_j} \times ... \times a_{d-1_k}\}$ where $0 \leq j \leq\mid a_0 \mid, ..., 0 \leq k \leq\mid a_{d-1} \mid$ with total number of members $\mid l \mid=\mid a_0 \mid \times ... \times \mid a_{d-1} \mid$.
5) S identifies a set of slices where $S = \{s_0, ..., s_{m-1}\}$ and $m = |S|$.
6) for every slice $s_s \in S$, s_s represents an area identified with $d-1$ aspects where $s \in \{(a'_0...a'_{d-2}) \mid a'_i \in A\}$
7) a graph $G_{n_l} = (V_{n_l}, E_{n_l})$ represents a graph in net n_l with set of vertices V_{n_l} and edges $E_{n_l} \subseteq V_{n_l} \times V_{n_l}$
8) $E_N \subseteq V_{n_{l'}} \times V_{n_{l''}}$ for each $n_{l'}$, $n_{l''} \in N$ defines all intra- and inter-net edges.
9) V_N represents vertices in the set of nets N where $V_N = \{V_{n_0} \cup ... \cup V_{n_{p-1}}\}$
10) $\mathcal{G}$ shows a set of graphs of all nets G_{n_l} where $\mathcal{G} = \{G_{n_0}, ..., G_{n_{p-1}}\}$

We present our multidimensional model illustrated in Figure 1 as an example of our approach. Here, our multidimensional model contains three aspects $A = \{$network level, depth, technology variants$\}$. Each aspects a_i has the following values $a_{\text{network level}} = \{$physcial infrastructure, network layer, E2E topology$\}$, $a_{\text{depth}} = \{$core Internet, access, home backbone, home edge$\}$, and $a_{\text{technology variants}} = \{$RBB, LTE/4G/5G, ethernet, 802.15.4,...$\}$. The nets are Cartesian product of values of each aspect, such as the physical infrastructure layer of the Internet core with a particular technology or the physical infrastructure of the home edge with Bluetooth. A slice defines all nets with different aspect values except one. We can identify three main slices in Figure 1: *network level-depth*, *network level-technology variants*, and *depth-technology variants* slices. Each slice identifies with two features such as network level and depth in our model. Note that, each slice shows a cross cut of the network for a particular value. Therefore, we may define parallel slices in each direction for different values. The network level-depth slice represents all network levels for each part of the network containing the Internet core, access, and edge networks. The network level-technology variants slice illustrates what technology variants and protocols can be utilized in each network level. Finally, the depth-technology variants slice shows the technology variants used in each part of the network.

Given our multidimensional smart-home model illustrated in Figure 1, consider the following example as a way of understanding the fruitfulness of our framework. Let's suppose that an edge network here is an end-user network connecting IoT devices to the Internet. A home network is one variant of the edge network. If we limit our representation to the physical structure of the home network and consider technology variants, we can identify various technologies such as WLAN, Bluetooth, and ZigBee. Each technology network has its own characteristics which can be represented as a separate graph interconnected to other technology networks. Such graphs with corresponding nodes and edges can be represented by separate nets in our framework. This information is also mapped to the *depth-technology variants* slice. Since the order of the nets representing each technology is not important in this slice, we can place non-IP after IP-based technologies to show their deeper order in the edge network by defining *home-edge* value for the depth aspect, the way that we showed in Figure 1. We can easily add another aspect such as power grid as an example to study the components of the communication network and the power grid together.

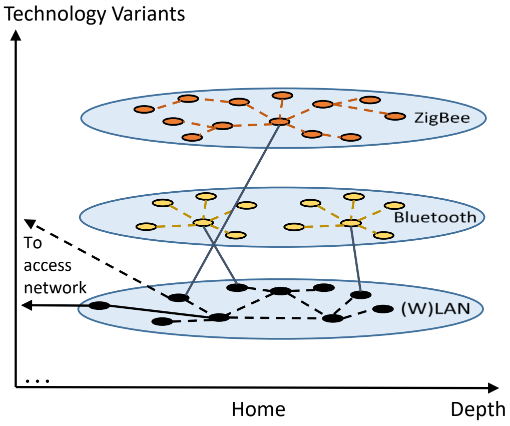

Fig. 3. Depth-technology variants

III. TECHNOLOGY INTERDEPENDENCE GRAPH ANALYSIS

In a multi-technology system, various networks with different characteristics can be organized in order to improve the resilience of the overall network. In such networks, a node or link failure may have different effect on the overall network depending on how the distinct technological networks are connected. For example, a catastrophic Bluetooth network failure usually will not affect other networks, such as ZigBee, in the same larger network. In order to understand the overall behavior of multi-technology networks, we believe that the dependence relationships between the distinct technologies can be understood as part of a comprehensive system-wide analysis.

We define the *technology interdependence graph* as a graph representing the interdependency of technology variants in a multi-technology IoT environment. We obtain the technology interdependence graph as the result of *one-mode projection* over a bipartite graph illustrating the relationship between each node and the supported technologies in a particular network such as a smart home or city [14]. The technology interdependence graph considers two aspects of a network: overall physical infrastructure and technology variants.

Assume that in a smart environment such as a smart home, we have nodes supporting various technologies including LAN, WLAN, and Bluetooth. Each group of nodes with a particular technology builds a physical structure. Some nodes in the physical structure such as a cell phone support various technologies including LTE and WLAN. Such nodes contribute to connecting diverse technologies together. If we consider the *nets* representing the physical structure of each technology as a single node and each connection between nets as an edge, we can represent the technology interdependence graph from our multidimensional framework intuitively.

Consider a typical smart home with two scenarios and nodes supporting LAN, WLAN, Bluetooth, ZigBee, LTE, and WAN technologies. An instance of the corresponding smart home graph is illustrated in Figure 4. Edge colors in the figure represent a particular technology such as cyan for Bluetooth. The smart home network is connected to the Internet with two different paths through nodes *DSL* and *Phone1*, which promotes network connectivity and consequently network resilience. The corresponding technology interdependence graph is illustrated in Figure 5. This graph shows the technology interdependence graph for scenario 1 when the *red* edge between *Phone1* and *BT1-0* is not connected.

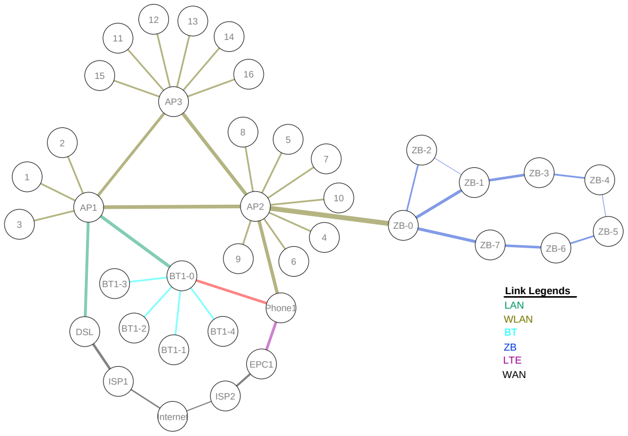

Fig. 4. Home end-system technology graph

In scenario 2, we assume that *Phone1* makes a new Bluetooth connection to *BT1-0* indicated with *red edge* in Figure 4. This edge connects two nodes. However, much more importantly it connects two technologies. This results in changes to the robustness of the overall technology interdependence graph illustrated in Figure 6. A simple comparison between Figures 5 and 6 shows that Bluetooth technology connects to more technologies and that it appears to make the whole network more robust to link failure. We observe that all technologies except ZigBee in Figure 6 are k-connected where $k \geq 2$. Calculating the network core for $k = 2$ confirms the result. Therefore, any single link failure between two technologies, except between ZigBee and WLAN, keeps the network connected.

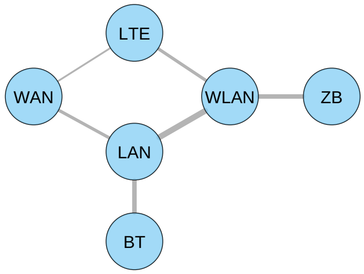

Fig. 5. Home technology interdependence graph

k-connectivity is one of the prime factors to promote network resilience due to providing path diversity. In multi-technology networks such as smart home and other smart environments, k-connectivity should also be considered among technologies in order to promote overall network resilience.

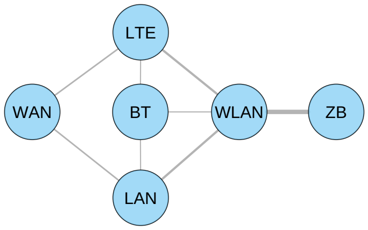

Fig. 6. Home technology interdependence graph

In the following, we show how to use the technology interdependence graph to study the properties of the overall network. In order to do that, we construct the corresponding graph of a smart home network with Python NetworkX [15]. For this analysis, we choose the graph in Figure 4 with two scenarios mentioned above when the red edge in the graph is available and when it is not. We calculate the technology interdependence graph based on the technologies each node supports obtained from the smart home graph. We calculate various centrality metrics including degree, betweenness and eignvector before starting our experiments for coordinating a targeted attack. We investigate the availability of technologies during nodes and links failure. The centrality metrics do not consider the type of each edge. For instance, degree centrality which considers the normalized number of connected edge to a node does not consider the type of each edge supporting a particular technology. Sometimes a high degree node is a proper target in a targeted attack to disrupt a network such as the master node in a Bluetooth network, or an access point in a WLAN. However, in a multi-technology network a low degree node may have more effect on the connectivity of a network. For example, disabling a DSL modem with degree of two can obviously disconnect the whole network from the Internet.

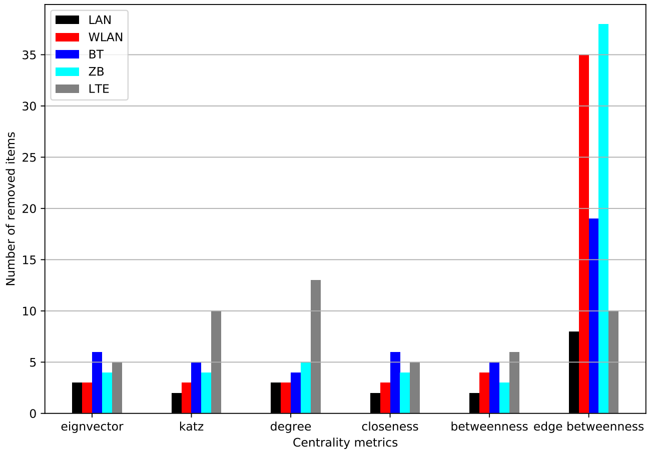

Fig. 7. Targeted attack based on centrality analysis for scenario 1

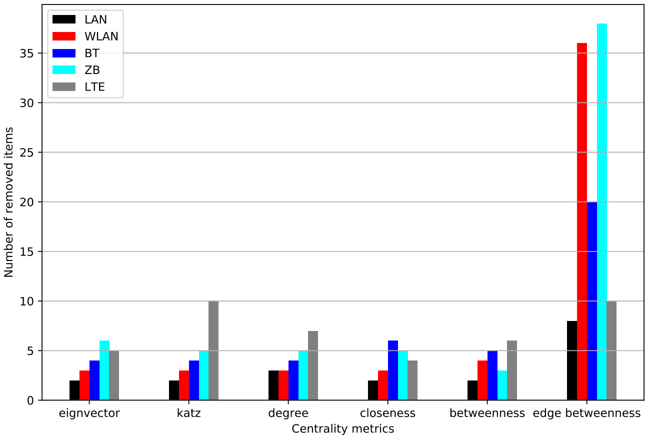

Fig. 8. Targeted attack based on centrality analysis for scenario 2

Figure 7 illustrates targeted attack based on centrality metrics analysis. In a percolation process, nodes and edges are added to a network to increase robustness and resilience. The inverse process can be used to measure the robustness of an available network by removing nodes and edges and measure the network connectivity. In this experiment, a particular centrality metric such as degree centrality is calculated for all nodes. Then, we remove an available node with the highest centrality value as the most important node based on that particular centrality metric. During the experiment, we do not calculate the centrality metrics again. This is due to the fact that, a smart home has a small size network and it partitions quickly by removing a few nodes and edges. However, while the network is partitioned some network technologies may still remain functional. Therefore, we cannot eliminate nodes and consider those nodes disconnected because they are in the smaller component of the network. Furthermore, most distance-based centrality algorithms cannot provide a correct result on a partitioned network. However, we eliminate nodes if they are not connected to any other nodes after each failure. We also assume that losing the ZigBee coordinator and the Bluetooth master node disrupts the corresponding network.

Figures 7 and 8 show the centrality analysis results for both scenarios of Figure 4. We use the following centrality metrics:

- *Eignvector* measures the importance of a node regarding its connectivity to other important nodes.
- *Katz* is an extension of eignvector considering a value to represent the importance of each node.
- *Degree centrality* is the normalized number of connected edges to each node.
- *Closeness* is the inverse of the average shortest paths between a particular node v_i to other nodes in the network.
- *Betweenness* measures the fraction number of the shortest path between every node v_i and v_j traversing on a node v_k
- *Edge betweenness* uses the same measurement as betweenness for every edge e_{ij}

Most of these metrics are node-based centrality metrics with the exception of edge betweenness. Edge betweenness also provides the worst results among other metrics under consideration. One reason is that when a node fails, all edges connected to the node fail as well. Therefore, the whole network fails faster than edge-based failures. In most experiments, we observe that the whole network fails after failure of 6 important nodes in the network. Note that, disruption of the LAN network, which also provides connectivity to the WAN modem, disconnects the network from the Internet. Thus, although many other technologies are operational, all the cloud-based services are disconnected.

Another important result is that in the first scenario LTE technology, provided by *Phone1* in the network with degree centrality two, fails after removing more nodes compared to the second scenario. The reason is that the most number of nodes in the graph have degree one or two. Activating Bluetooth in *Phone1* changes the node degree from two to three which makes the node more important in scenario 2. Since our network has two paths to the Internet through WAN and LTE technologies, in the first scenario, it takes longer time that the whole network is disconnected from the Internet. This is due to the fact that degree centrality does not consider the variety of the technologies represented by edges. This effect can not be observed in a flattened network, but it is evident in a multidimensional network. A node supporting multiple types of technologies works as a bridge among various network technologies. Therefore, if the node provides the only connection among technologies, failure of such a node may disconnect many network technologies. As an example, if the only access point with many clients in a network fails, it disrupts WLAN; however, if a cell phone supporting two active technologies LTE and WLAN fails, the path between two technologies is disconnected. Therefore, we propose a degree-based centrality related to variety of edges for confirmation.

We consider degree centrality of each node v_i as a fraction of the supporting technologies in a network in a way that $d'_i = d_i \times (s_i/t)^\alpha$ where t is the overall number of supporting technologies in a network, s_i is the number of technologies that node i supports, and d_i is the traditional degree centrality value of v_i. α is an optional exponent to magnify the effect of the various number of technologies. This calculation assigns a higher value to a node v_i with degree d_i supporting s_i technologies than another node with the same degree but $s_j < s_i$ supporting technologies. Figure 9 shows the degree centrality results for scenario 1 with our proposed method, *degree variant*, and the conventional degree centrality method.

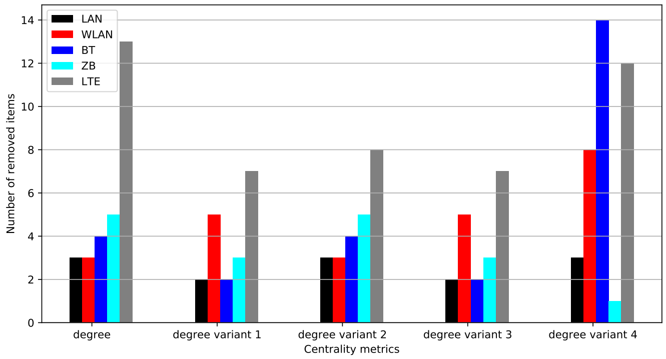

Fig. 9. Degree centrality variants for scenario 1

As shown in the figure, *degree variant 1* shows better result compared to the conventional degree centrality calculation. The result shows that the nodes with supporting more technology variants are targeted first, even if they have a lower degree centrality.

We also examine three other degree centrality variants illustrated in Figure 9. *Degree variant 2* calculates centrality as $d'_i = d_i + d_i \times (s_i/t)^\alpha$. *Degree variant 3* considers centrality as $d'_i = d_i \times (s_i)^\alpha$. We use different approach in *degree variant 4*. First, we remove all nodes with one neighbor, and then we calculate degree centrality based on the new graph. We follow this approach to decrease the centrality value of nodes that increase by connecting to less important nodes; however, the result is not as promising as degree variant 1.

IV. CONCLUSION AND FUTURE WORK

In this paper, we present our multidimensional model as a framework to facilitate the representation of multi-technology networks with various aspects. Then, we explore a smart home model as an instance of our multidimensional model. We observe that considering a technology interdependence graph along with multidimensional model of a network can give us a better understanding of interdependency of multi-technology networks. This result helps us to propose a modified degree centrality metric to explain the structure of networks. In future work, we plan to study other centrality metrics in multi-technology networks such as smart homes and cities.

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