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發展一般化蜂巢環圈網路以應用在智慧型隧道偵測控制資料擷取(SCADA)網路之設計為例

國立交通大學管理學院運輸科技與管理學系博士論文

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摘要

一般環形網路(度數(degree)為二)往往考量有一條"節線"容錯(fault tolerance)的特性與提供可有序地查核維修的機制，但對於網路上"節點"之破壞防患通常最多僅考量備份(spare)的觀點，但備份的節點在平時並未構成整體營運的一部份，一旦事變其啟動時差等因素會影響即時應變的能力；本論文提出節點成對、度數為三的蜂巢矩形環圈(HReT, honeycomb rectangular torus)與一般化蜂巢環圈(GHT, generalized honeycomb torus)網路模式供隧道內偵測控制資料擷取(SCADA)網路之應用。本論文數學証明蜂巢矩形環圈網路的特性：證明蜂巢矩形環圈上任一節線斷落，網路上各節點可維持漢彌頓特性；在縱向節點數目至少為六或橫向節點數目僅為二但縱向節點數目至少為四的狀況，證明蜂巢矩形環圈上任一對異性之(biparpite)節點損壞，網路上其他各節點仍可維持漢彌頓特性。本論文數學証明一般化蜂巢環圈網路的特性：証明蜂巢矩形環圈、蜂巢環圈(HT, honeycomb torus)可以同構成一般化蜂巢環圈網路；蜂巢環圈可屬一種管形之一般化蜂巢環圈網路；並證明管形之一般化蜂巢環圈網路可保有環狀之漢彌頓特性，有利於在單管形空間配置同時具有節線與節點容錯性暨提供可有序地查核維修的機制。

(June, 2003)

Developing Generalized Honeycomb-Torus Networks and the Application in Intelligent Tunnel SCADA Networks Design

Dissertation of Department of Transportation Technology & Management
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Abstract

The ring network of regular degree-2 nodes is generally utilized for links' fault tolerance as well as providing a mechanism supporting orderly inspection and maintenance, and spare may be arranged to support nodes' fault tolerance. However, spares are inefficiently used in normal conditions and may have difficulties to support real-time processing. Therefore, in this dissertation, HReT (honeycomb rectangular torus) and GHT (generalized honeycomb torus) networks of degree-3 dual-nodes are studied for promoting the capability of the SCADA (Supervisory Control And Data Acquisition) network in tunnels. The following HReT network features are mathematically proved: HReT (m,n) is 1-edge hamiltonian, and HReT(m,n) is 1_p-hamiltonian if and only if either $n \geq 6$ or $m = 2$ and $n \geq 4$, HReT(m,n)-F can keep hamiltonian when F={a,b} with a in A and b in B, A and B are bipartite nodes' groups. The following GHT network features are mathematically proved: HReT network and HT (honeycomb torus) can be isomorphic to GHT network, and HT can be a specific single-tube shaped GHT which can keep hamiltonian when one edge is broken and have both links' and nodes' fault tolerance as well as a mechanism supporting orderly inspection and maintenance.

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Chapter 1

Introduction

1.1 Research Background

Instead of the list–shaped network with degree–1 end nodes, the ring–shaped network of regular degree–2 nodes is generally considered for links' fault tolerance as well as providing a mechanism supporting orderly inspection and maintenance of the network. However, the ring configuration has difficulties to support nodes' fault tolerance; therefore, arranging spare facilities for fault management is considered in some networks.

However, spare nodes can have difficulties in supporting real–time processes in very urgent conditions and they are inefficiently used in normal working conditions. Therefore, in this dissertation, the networks of dual–nodes, which are similar to the human's two eyes, are intended to study for promoting the capability of information–acquisition as well as the fault tolerance of both nodes and links.

Therefore, degree–3 networks of dual–nodes are established for possible applications in tunnles' SCADA (Supervisory Control And Data Acquisition) networks; their features regarding fault tolerance of both nodes and links and the hamiltonian property to support orderly inspection and maintenance are intentionally studied through mathematical proofs to offer the foundation of safety / quality assurance.

1.2 Research Motives

Serious tunnel accidents are not scarce from the global viewpoint. In Taiwan, for example, its new subway system of Taipei metropolis has at least got two serious damages. One is in 1999; a new building construction cleaved the adjacent tunnel structure (Chang, 2001). The other is in 2001; the flood due to a typhoon ruined its main control center.

We believe careful management and design can well protect most tunnel accidents. However, from the following case, considering unexpected faults and efficient maintenance seems to be worthwhile for at least disaster sensitive tunnels. In November 11, 2000, about 170 peoples lost their lives in a fire disaster of a cable-driven-car tunnel in Kaprun, Salzburg, Austria. It happened 6 months after the Tauern Tunnel disaster close to the portal of Salzburg (Leitner, 2001), and 8 months after the disaster of Mont Blanc Tunnel between France and Italy. The governor of Salzburg said, "It is completely incomprehensible because no faults have ever been found; the last check was just a few weeks ago." (Washington Post, 2000, Nov., 11)

Since a 12.9–km–long road tunnel, the Snow–Mountain tunnel, is being constructed in Taiwan now, and its disaster–sensitivity cannot be overlooked, this dissertation also hopes to strengthen safety assurance for our country fellows in time. It should be noted that when such a master–piece project is getting prepared for traveling, people will begin to more concern about tunnel's security system whether it can assure users' safety in its rather close and narrow environment for taking at least about 10 minutes' passing time.

1.3 Research Objectives

Based on the mentioned research motives, three objectives are aimed for this dissertation research.

(1). Proving model networks being able to have both links' and nodes' fault tolerance, as well as have a mechanism of sequential order for inspection and maintenance. In another words, proposing model networks of dual nodes, whose node degrees are

3; then proving those model networks at least can keep hamiltonian when a link is broken or two adjacent nodes fail.

(2). Providing alternative network patterns to fit various tunnel types and adaptability for individual needs, such as zoning, of a tunnel design.

(3). Promoting safety or quality assurance for the coming Snow–Mountain tunnel in time.

1.4 Research Scopes

In the following, the scopes of research are outlined for clarifying our research intentions, expected objectives or features for potential application.

It is intended to integrate intelligent networks within tunnels for assuring safety and quality; offer the control center of a tunnel an information processing and environmental control network having systematical fault tolerance as well as a mechanism for efficient inspection or maintenance, which are much concerned for those having disaster sensitivity, such as lengthy tunnels. Hence, providing mathematical proofs of those network schemes to solve those issues are chief interests of this dissertation.

This dissertation is a research of searching the network models which can naturally have attributes for network security on the level of system architecture, and can not only be potentially well applied for large–scale tunnel developments but also can be adapted for general various tunnel types.

In this network research, the node or vertex represents the information unit, whose supervisory control items, distributive densities or patterns can be adapted based on individual physical concerns; the degrees of the link or edge may be increased based on zoning requirements or other demands.

1.5 Research Processes

There are six processes can be summarized as follows, and conceptually presented as Figure 1.1.

1.5.1 Background and affiliated knowledge understanding

The following knowledge should be prepared as basic foundations for this research.

(1). To learn related knowledge of network topology.

(2). To study the interrelationships between information processing efficiency and network architectures.

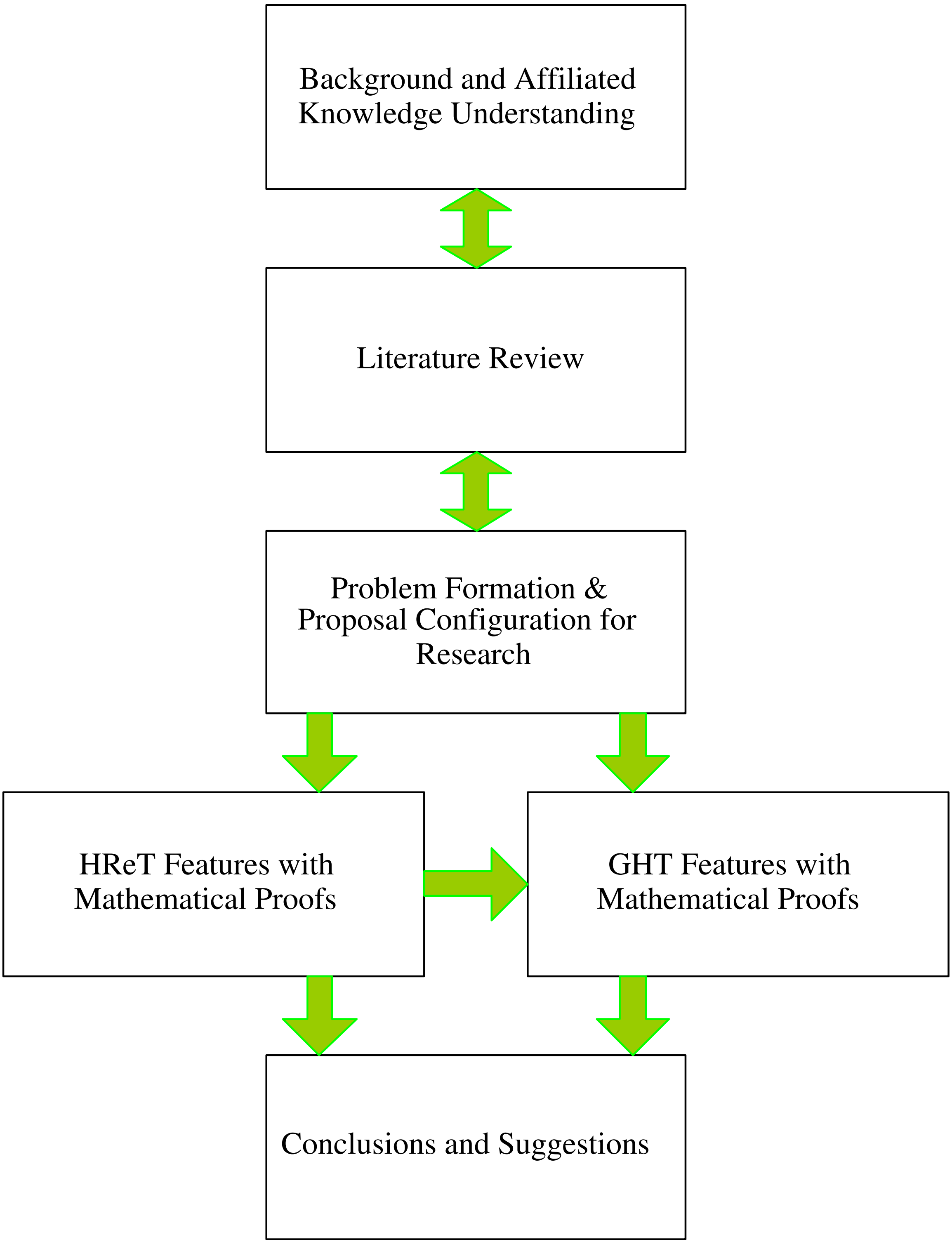


Figure 1.1: Conceptual Flowchart of Research Process

(3). To understand the demand of fault tolerance and some related researches.

1.5.2 Literature review as the second process

Literature review will contain the following directions:

(1). To search and understand potential network configurations which can have fault tolerance.

(2). To study the index of fault tolerance or what extent can be called having fault tolerant capability; their persuasive contexts or related methods for proving fault tolerance should be reviewed.

(3). To understand the seriousness, chief protection methods, potential reasons or causal relationships of tunnel disasters.

1.5.3 Problem formation and proposal configuration for research

Main considerations in this area are summarized as follows:

(1). Since once the capability of tunnel disaster prevention can be assured by mathematical proof or scientifically evidence, related transportation management or policies could be rather easier promoted. Therefore, establishing network architectures based on mathematical proofs are identified for the main direction of this dissertation.

(2). Since long tunnels generally have rather higher disaster sensitivity, therefore, the factor of large–scale should be identified as the important point for developing a prototype network model for securing tunnels; however, it does not mean the individual adaptability can be overlooked.

(3). Since the objective of this research will essentially consider both nodes' and links' fault tolerance, as well as a sequential order of inspection and maintenance for tunnels' security networks; therefore, other disaster sensitive tunnels, such as: under–water tunnels, or high–speed–rail tunnels can potentially be applied.

(4). Since parallel two tunnels, they and independent single tunnels are considered two main kinds of tunnels, need be coordinated for urgent conditions; they can be looked like a run–track shape from 2–D view or an extended but narrowed torus from 3–D view, if their ends are network connected; therefore, HReT (honeycomb rectangular torus, see Chapter 2) network is proposed as the prototype for parallel two tunnels.

(5). Since HReT can be rotated 90 degrees, HReT network can also be proposed as the prototype for independent single tunnels, such as high–speed–rail tunnels which should well coordinate information acquisition and supervisory control of both upper and lower monitored points; moreover, GHT (generalized honeycomb torus, see Chapter 3 and 5), which is derived from the isomorphism of the honeycomb torus, can probably be proposed as the prototype for independent single tunnels with fault tolerance demand.

(6). Multiple tunnels basically can be composed by the above patterns mentioned in (4) and (5).

(7). Since building disaster sensitive tunnels with highly assured quality should be an important work or a cornerstone for developing ITS (intelligent transportation systems), the network model in the tunnel can be coordinated with main supervisory control and data acquisition tools of ITS. Especially CCTV, as a featured example, can provide clear information and can be digitally processed or quickly analyzed by state of the art. Moreover, since CCTV still may need rather larger memory and CPU time, therefore; one CCTV camera can be connected to one terminal as one node of the network, and can establish up a SCADA network based on the regular degree–3–node prototype pattern mentioned in (4) and (5) and can naturally have distributed intelligence based on network's cooperative or parallel processing functions (Bickel, 1996, p.490–495).

1.5.4 HReT features with mathematical proofs

The main contents are as follows:

(1). It is assumed that the network has positive even numbers of nodes in both column and row directions. The defined row direction needs at least 4 arrays of nodes; however, this requirement can be neglected for real tunnel application.

(2). We prove that any HReT can keep hamiltonian when an edge is broken.

(3). If the defined row direction has more than 6 arrays or the defined column direction has only 2 arrays, it is proved that any pair of bipartite nodes fail, the HReT network can keep hamiltonian.

1.5.5 GHT features with mathematical proofs

The main contents are as follows:

(1). To prove that the honeycomb torus is isomorphic to a kind of GHT network, which is a bipartite and degree–3 network. The honeycomb torus has already been proved: (a). It is hamiltonian (Megson, Yang and Liu, 1999). (b). Even two adjacent nodes fail or one edge is broken, it can keep hamiltonian (Megson, Liu and

Yang, 1999).

(2). To prove that the HReT network can be considered as a special type of GHT network.

(3). To prove that the certain shaped GHT networks, can keep hamiltonian when an edge is broken or two adjacent nodes fail.

1.5.6 Conclusions and suggestions

The last process of this dissertation is to summarize or briefly discuss the results of previous processes or make conclusions and suggestions.

1.6 Epilogue of this Chapter

In the next chapter, we will review literatures on related network topology and tunnel issues. In Chapter 3, we will prove that the HReT network can keep hamiltonian "when one link is broken" or "when two nodes of mathematically different corresponding parties are broken". In Chapter 4, we will prove that the certain shaped GHT networks can keep hamiltonian when an edge is broken or even two adjacent nodes fail, and the HReT network and the honeycomb torus can be isomorphic to the GHT network. In Chapter 5, we will discuss tunnel issues, then establish torus–based networks by graphs and propose them for tunnels. The HReT network is proposed for critical single or parallel running tunnels. The adapted GHT network is proposed for service or other tunnels. Finally, in Chapter 6, we will make conclusions and suggestions.

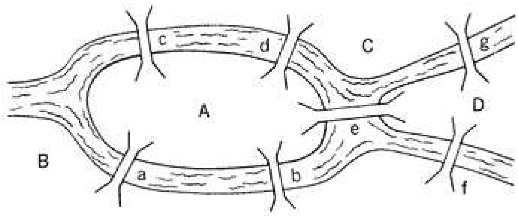
Chapter 2

Literature Review on Network Topology

2.1 Foundation idea of topology and this Dissertation

The network configuration needs to coordinate with its circumscribed physical environment; therefore, the shape of tunnel spaces as well as their funtionally required networks should be analyzed together. Hence, the study concerning network shapes, such as so–called network modeling, graph theory or topology is considered first for this research. These titles of the above studies are different; however, their contexts related to the scope of this research is basically same or closely related.

Topology is the branch of mathematics that deals with patterns involving position and relative position. Geometry also deals with position, but the geometer or classical geometry is concerned with measurable quantities such as angles, dis-



Source: Encyclopedia Americana

Figure 2.1: Illustration of Konigsberg Bridge Problem

tances, and areas, whereas topology is concerned with properties of continuity and relative position that are independent of such magnitudes, and hence, topology is some–times known as the geometry of position.

Since topology studies properties of spaces that remain unchanged, no matter how the spaces are bent, stretched, shrunk, or twisted, hence, such transformations of ideally elastic objects are subject only to the condition that nearby points in one space correspond to nearby points in the transformed version of that space. The essence of the above concept is important for sketching the scope of this research. Since most tunnels can be considered as a tube or a pair of parallel tubes, which can have different dimensions or may be curved or with some other varieties.

Moreover, the scope of this research is also aimed at offering the control center of

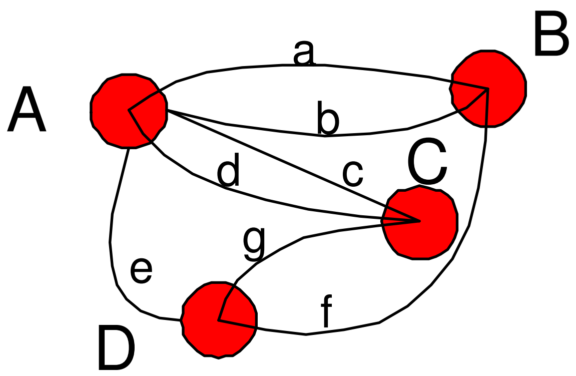


Figure 2.2: Network Presentation of Konigsberg Bridge Problem

a tunnel an information processing and environmental control network having fault tolerance as well as a mechanism for systematical efficient inspection or maintenance, which are much concerned for those having disaster sensitivity, such as long tunnels. The related analysis on features or rules of various network prototypes has been studied in the papers related to network topology and will be discussed in the following subsection. Some other concepts of related foundation idea of topology and this dissertation are shown below; similar contents can be found in many books, including Bondy and Murty, 1980.

The first topology article is the Konigsberg (now Kaliningrad of Russia) Bridge Problem published in 1736 by Swiss mathematician Leonhard Euler (1707–1783),

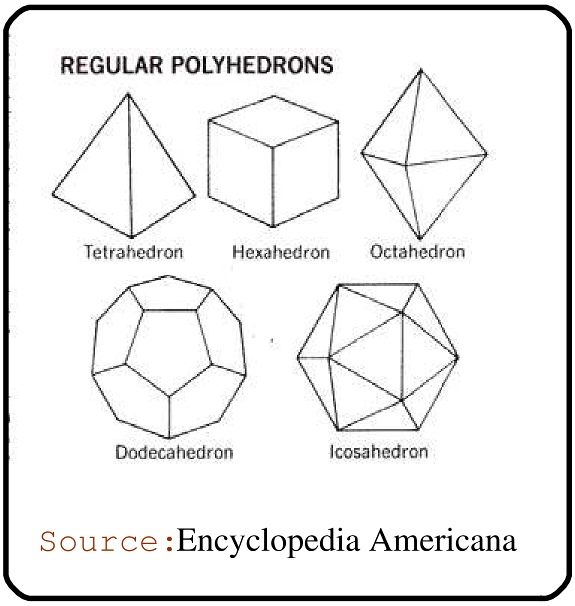


Figure 2.3: Dodecahedron and Other Polyhedrons

which is entitled "The Solution of a Problem Pertaining to the Geometria Situs". The problem, shown as Figure 2.1, 2.2, is "At Konigsberg, the river Pregel surrounding an island is divided into two branches. Over the branches of this river lead seven bridges. Is it possible to cross each bridge once and not more than once in a continuous walk?" Euler presented this problem by using a node to represent a land and a link to represent a bridge. Euler proved that solving this problem is impossible.

The concept of this problem has inherently importance to this dissertation. The

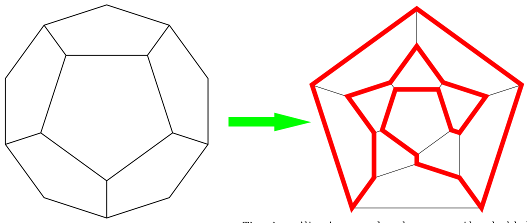


Figure 2.4: Dodecahedron's Hamiltonian Cycle of All Nodes

number of edges incident with a node is called the degree of the node. To solve Konigsberg bridge problem, the degree of each node should be even, or the number of in–degree should be the same as the number of out–degree. However, the degree of each node of Konigsberg bridge problem is odd; therefore, this problem cannot be solved without recrossing any bridge. In graph theory, a tour containing all the links of a graph exactly once is called eulerian.

A contrasted concept is also worthwhile for this dissertation. A cyclic tour containing every node of the graph exactly once is called a hamiltonian cycle. This property can also be called hamiltonian, and the problem need not pass all the links. This property is widely applied in information processing and management, and is derived from a game designed by an Irish mathematician, Sir William Rowan Hamilton (1805–1865) in 1856. Hamiltonian labeled each node of a dodecahedron with the name of a well–known city. The objective of the game was for the player to travel "Around the World" by arranging a round trip which included all the cities exactly once through the edges of the dodecahedron. This problem can be solved, or its hamiltonian cycle exists, see Figure 2.3, 2.4. However, for a large–scale network, the hamiltonian cycle may not exist and such problem belongs to an NP–complete problem (Dolan and Aldous, 1993, p.459).

The "Token Ring", topologically a broadcast ring, is considered as a featured application of the hamiltonian property, which devises a cyclically communication order to process information; therefore, it can keep a high processing rate and avoid the slowdown due to occasional overloads which may happen in the previous Ethernet, a bus broadcast system. For the scope of network configuration, its hamiltonian property means all the nodes (as functionally distributed information processing or controlling units) can be connected cyclically, so that the data can be sequentially transferred or processed, and this property also can significantly benefit for organized inspection or maintenance work. If we want to search for the most efficient hamiltonian cycle, then this problem will be the so–called traveling salesman problem. However, this research basically concern the network issues of information processing or communication, the length of a link can have very limited effects. Hence, the search for the most efficient hamiltonian cycle is rather not important for this research.

2.2 Review on distributive network topology

The network for information processing has become increasingly important, because it makes individual processors much more useful. In this dissertation, the network for information processing or communication is physically distributed in rather narrow but lengthy spaces. In the following, some typical network topologies, which can help parallel processing or systematically coordinating of whole processing units will be reviewed. Moreover, some concepts of adaptation for physical spaces will be illustrated.

Many interconnection topologies have been proposed in the literature for the purpose of connecting a large–scale processing elements (Leighton, 1992). Network topology is always represented by a graph where nodes represent processors and edges represent links between processors. One of the most popular architectures are the mesh–connected computers (Leighton, 1992). Each processor is placed in a

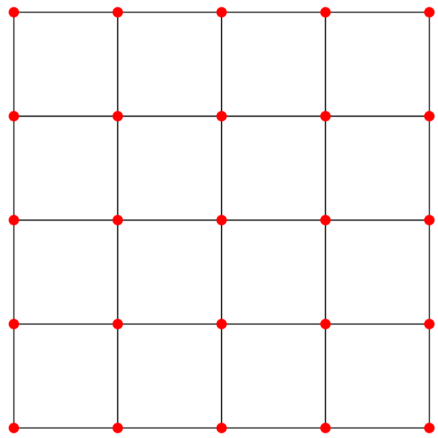


Figure 2.5: Square Mesh Network

square or rectangular grid and is connected by a communication link to its neighbors up to four directions.

It is well known that there are three possible tessellations of a plane with regular polygons of the same kind: square, triangular, and hexagonal, corresponding to dividing a plane into regular squares, triangles, and hexagons, respectively (see Figure 2.5, 2.6, 2.7). Based on this observation, some computer and communication networks have been built. The square tessellation is the basis for mesh–connected computers. The triangle tessellation is the basis to define hexagonal mesh multiprocessors (Chen et al, 1990, Youn and Lee, 1996). The hexagonal tessellation is the

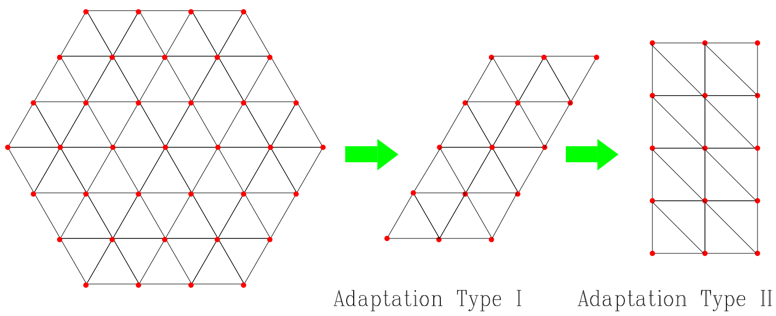


Figure 2.6: Hexagonal Mesh Network

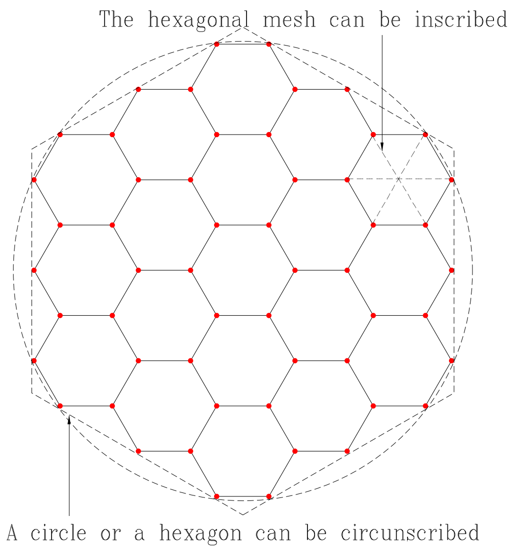


Figure 2.7: Honeycomb Mesh Network

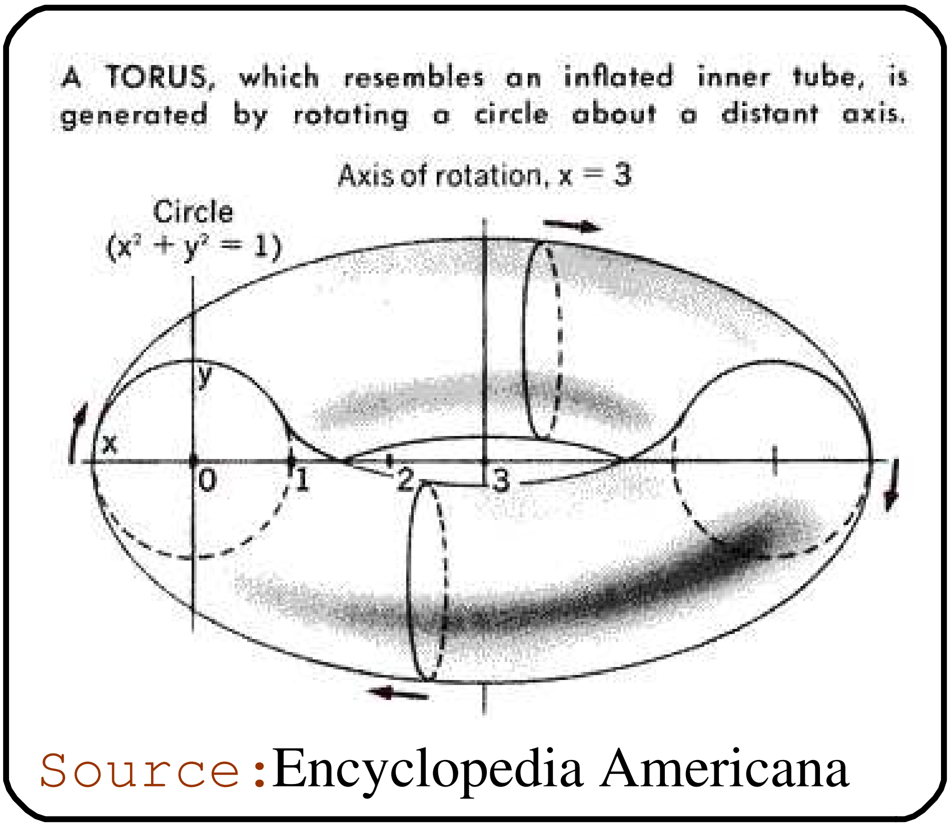


Figure 2.8: Torus Geometry

basis to define the honeycomb meshes (Carle et al, 1999, Stojmenovic, 1997).

Tori are meshes with wraparound connections to achieve vertex and edge symmetry. Meshes and tori are among the most frequent multiprocessor networks available on the market. The torus was historically first studied more than two thousand years ago. In mathematics a torus is formed in three-dimensional space by rotating a circle about a line that is in the same plane as the circle but does not cut or

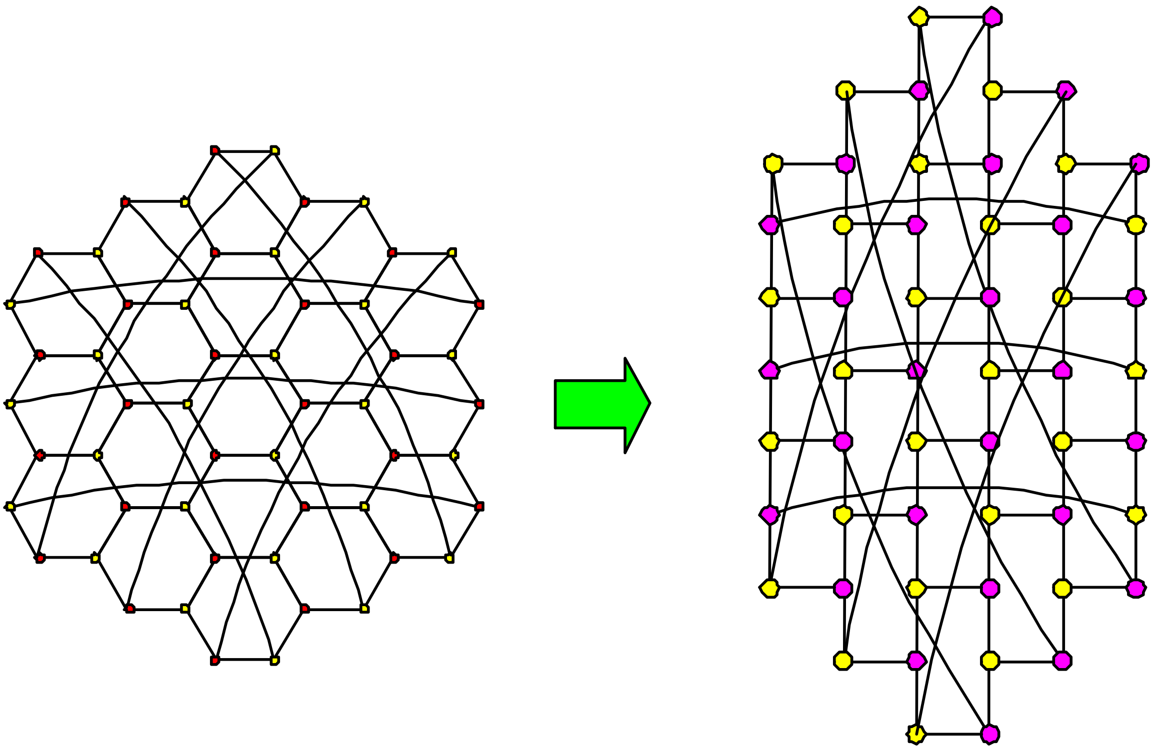


Figure 2.9: Honeycomb Torus

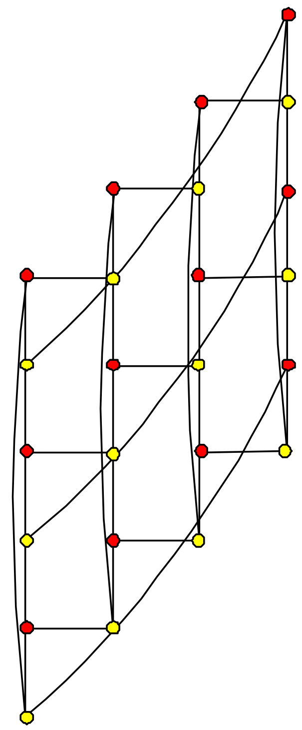


Figure 2.10: Honeycomb Rhombic Torus

Table 2.1: Degree of Common Networks

Network	Degree
mesh -connected computer	4
hexagonal mesh	6
honeycomb mesh	3
honeycomb rhombic mesh	3
honeycomb square mesh	3
torus	4
hexagonal torus	6
honeycomb torus	3
honeycomb rhombic torus	3
honeycomb square torus	3

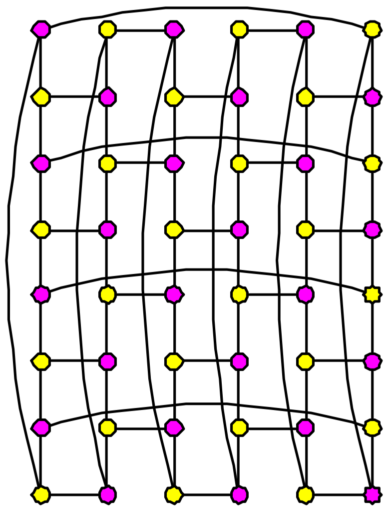


Figure 2.11: Honeycomb Rectangular Torus

touch it. The shape of torus likes the inflated inner tube of a tire or like a doughnut (Figure 2.8). However, in modern topology some deformations of it are considered.

The degree of a square mesh is generally four; however, the degree will be three or even two on its boundary. In other words, we may have difficulties to use regular algorithms to process information on all nodes; therefore, that network may be not economical or inefficient in some situation. Leighton, 1992, transformed the mesh into the torus with regular degree of four by adding wraparound links. In other words for visual thinking, first we can connect the upper and the lower edges of the square mesh to form a cylinder, then connect the left and the right ends of the cylinder to form a doughnut shaped torus network. This topology for computer network is considered as the basic tori shape, or we can simply call it "torus". Stojmenovic (Stojmenovic, 1997) also introduced the honeycomb tori by adding wraparound edges on honeycomb meshes, i.e. the honeycomb mesh and its adaptations (Figure 2.9, 2.10, 2.11, Table 2.1).

Recently, the honeycomb torus has been recognized as an attractive alternative to existing torus interconnection networks in parallel and distributed applications. Thus, there are a lot of studies on topological properties of honeycomb torus (Megson, Yang and Liu, 1999, Megson, Liu and Yang, 1999, Stojmenovic, 1997). The hamiltonian properties is one of the major requirements in designing the topology of networks. For example, the "Token Passing" approach is used in some distributed systems. Interconnection network requires the presence of hamiltonian cycle in the structure to meet the "token ring" requirement. Fault tolerance is also desired in massive parallel systems that have a relative high probability of failure. The hamiltonian properties of the honeycomb tori were studied by Megson, Liu and Yang. It is proved that all the honeycomb tori are hamiltonian (Megson, Yang and Liu, 1999). Moreover, there exists a hamiltonian cycle in any honeycomb torus with adjacent two faulty nodes (Megson, Liu and Yang, 1999).

The physical world is three–dimensional and the 3D view of Figure 2.11 can be like the geometry shape of a torus. However, similar to what we present all above 3D figures in the 2D paper, we can devise the aggregation of information processing in a plan and really produce them in a plane shape (Pahami and Kwai, 2001). However, the network topology will affect the physical shape of the whole aggregation (Stojmenovic, 1997, p.1037), the appearance of their products, and related costs or values.

Different goals or backgrounds will affect the results of system evaluation, this concept can also be applied for evaluating different network topologies. Generally, we can use the cost and the bisection width of the network architecture as the indices for evaluating network topology; the cost of the network architecture is the product of the network degree and the diameter, i.e., the longest steps of the shortest path to sequentially connect other nodes; the bisection width is the estimated cut links bisecting the network architecture. The cost is hoped to be less for economy, and the bisection is hoped to be more for network protection.

The network topology is generally adaptable. Stojmenovic, 1997, for example, hoped to coordinate both hexagonal mesh and honeycomb mesh and to form a kind of torus by wraparound after his comparison analysis. The hexagonal mesh can also be deemed as a rectangular mesh added with diagonal links, and its node analysis can be established on a general two–way rectilinear coordinate system. However, the hexagon based honeycomb mesh can intuitively have three directions. Stojmenovic, 1997, designed a three–direction but zigzag coordinate system (Z coordinates), and proved some interest properties. The nodes of honeycomb shaped networks can be divided into two parts. One, considered as white, is with the sum of three coordinates of 1; the other, considered as black, is with the sum of three coordinates of 2. The black and the white are interwoven. Therefore, the nodes have bipartite property (see Figure 2.12).

Bipartite is an offen–discussed topic in the field of graph theory; its application in network is considered in developing. For example, the Honda company of Japan has designed some dual devices for its featured products. Using a pair of devices instead of one can prevent totally out–of–order in some serious situations, and can strengthen product quality or its feature promotion. In Figure 2.13, a car proficient for driving in snow–covered field with its dual pump system is shown (honda.co.jp). Other similar applications can easily be found in many areas (such as: Chrest et al, 1996, p.127).

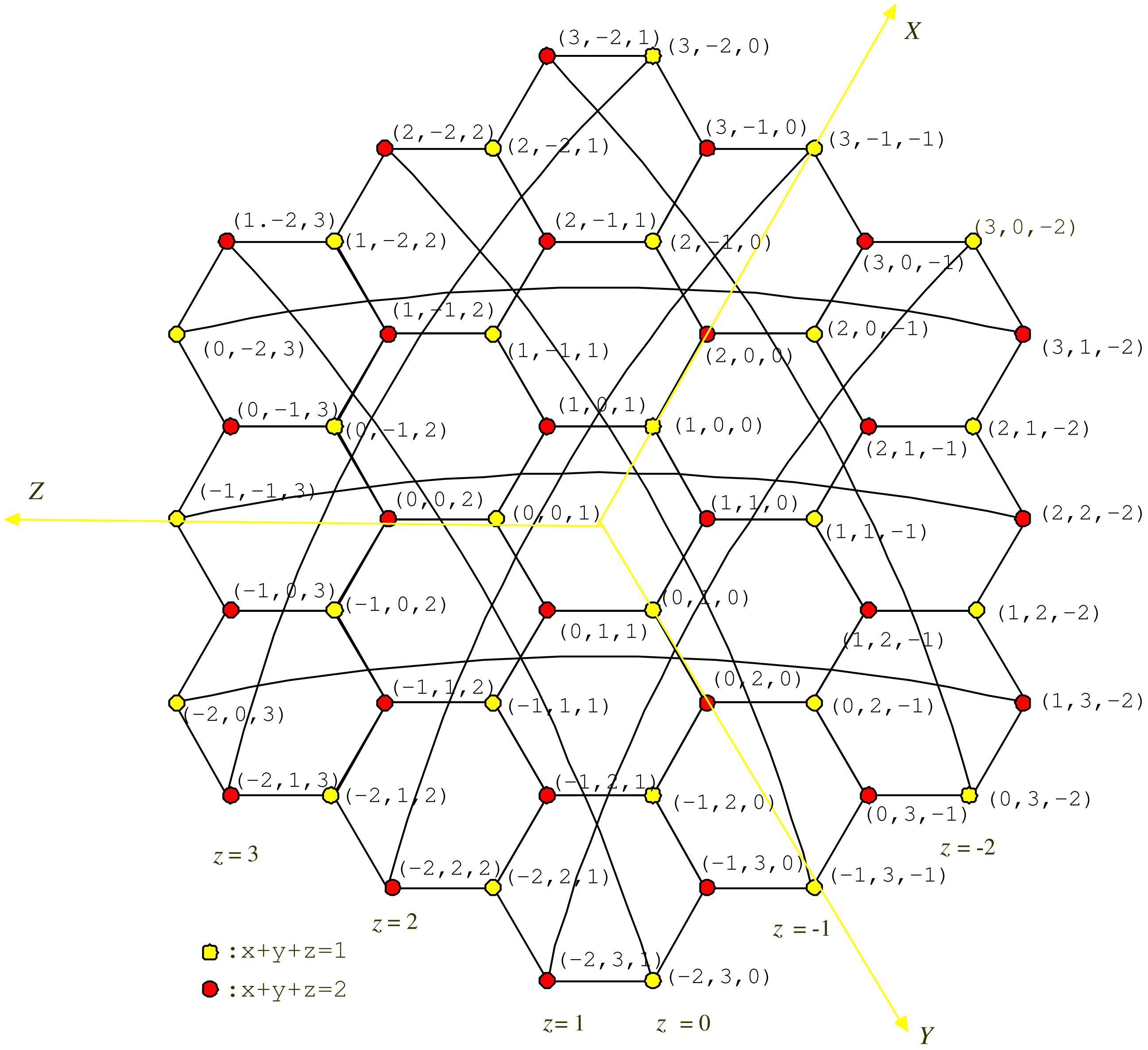


Figure 2.12: Honeycomb Torus and Its Z Coordinates

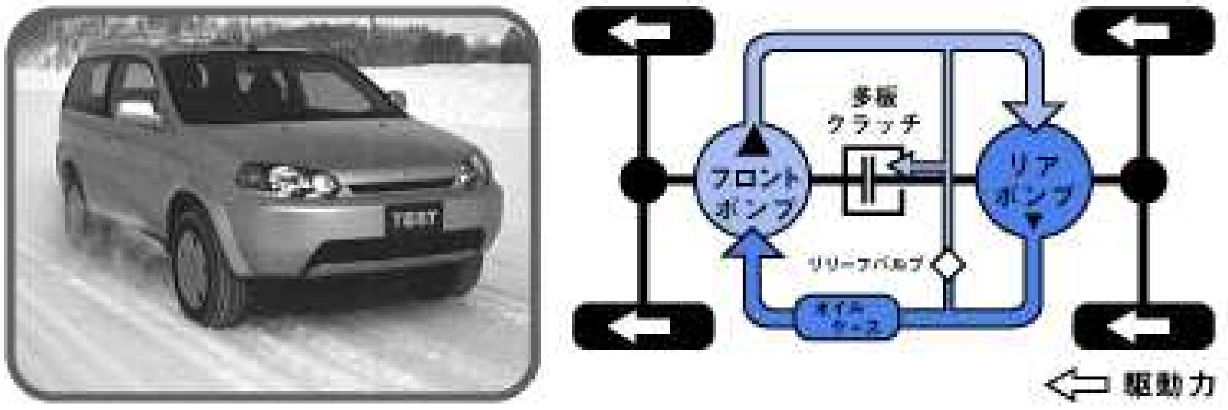


Figure 2.13: A Honda Car for Cold Area and Its Dual Pump System

The above dual–nodes concept is considered for nodes' fault tolerance. In network topology, generally links' fault tolerance is considered only. Stojmenovic, 1997 used bisection width as the index to evaluate it, and Megson, Liu and Yang evaluate it with whether exists a hamiltonian cycle in a network with a faulty link (or essentially adjacent two faulty nodes). In this dissertation, the latter is referred as the basic criteria for links' fault tolerance.

If the torus, or the honeycomb rectangular torus is straightened and enlarged, it is inherently the configuration of a pair of parallel tunnels connected by communication lines at both ends. In the mean time, since the honeycomb rectangular torus is derived from the honeycomb torus with similar attributes of network architecture, such as: closeness, expandability and regularity, it is considered worthwhile to study the honeycomb torus also. It can be found that the honeycomb torus can be an isomorphism of a tube shaped network; the isomorphism means that two graphs have one–to–one mapping relationship, then two nodes are adjacent in one graph, if and only if the mapping nodes of the other graph are adjacent. Both the honeycomb rectangular torus and honeycomb torus will be analyzed on hamitonian property and fault tolerance for our research purpose to develop intelligent SCADA (Supervisory Control And Data Acquisition, Bickel et al, 1996, p.495) networks for tunnels.

sectionSummary of this section In this literature review on network topology, the followings have been discussed:

(1). The origin and the definition of topology has been explained. The conceptual relationships between topology and the physical space or installed network of the tunnel is discussed.

(2). We have talked about what is degree and its meaning for a circuit containing all links or eulerian property.

(3). We have talked about what are the hamiltonian property and its possible efficiency benefits due to its sequential order without redundant procedures.

(4). We have introduced common computer network types and what is torus, and we have explained the concept of degree regularity and that it is the reason for developing torus networks.

(5). We have introduced the indices for evaluating the network topology, and explained that the honeycomb torus has potential competency and some directions for application consideration, including its bipartite property for dual–nodes network, degree regularity, potential economy or efficiency in processing, and fault tolerance.

(6). We have shown a simple but real example of dual–nodes network.

(7). We have introduced what is the isomorphism and it is a topic in the field of graph theory.

(8). We have talked about that both honeycomb torus and its derived honeycomb rectangular torus inherently have tube–shaped configuration, which naturally can coordinate the functionally required network with its physical space.

(9). We have introduced what is fault tolerance, and we can use the criteria of the accepted literature as criteria for our further research.

Chapter 3

Hamiltonian Properties of HReT Network

In this chapter, m and n are assumed positive even integers with $n \geq 4$. After basic definitions in Section 3.1, we present a recursive property of the ring embeddings in HReT(m, n) in Section 3.2. In Section 3.3, we discuss the ring embedding properties of HReT$(2, n)$. With the recursive property presented in Section 3.2, we can prove that any HReT(m, n) remains hamiltonian when any edge is faulty. In Section 3.4, we discuss the ring embedding property of HReT$(4, n) - F$ for any $F = \{a, b\}$ with $a \in A$ and $b \in B$. In the final section, we discuss the ring embedding properties of any HReT$(m, n) - F$ where $F = \{a, b\}$ with $a \in A$ and $b \in B$.

3.1 Definitions

Stojmenovic (Stojmenovic, 1997) introduced the honeycomb tori by adding wraparound edges on honeycomb meshes, the honeycomb rectangular torus is a specific kind of the honeycomb tori. The honeycomb torus has been recognized as an attractive torus, and its hamiltonian properties is a major requirements in designing the topology of networks. (Megson, Yang & Liu, 1999; Megson, Liu & Yang, 1999)

In this dissertation, a network is an undirected graph. For the graph definition and notation we follow (Bondy, 1980). $G = (V, E)$ is a *graph* if V is a finite set and E is a subset of $\{(a, b) \mid (a, b)$ is an unordered pair of $V\}$. We say that V is the *node set* and E is the *edge set* of G. Two nodes a and b are *adjacent* if $(a, b) \in E$. A *path* is a sequence of nodes such that two consecutive nodes are adjacent. A path is delimited by $< x_0, x_1, x_2, \ldots, x_{n-1} >$. We use P^{-1} to denote the path $< x_{n-1}, \ldots, x_2, x_1, x_0 >$ if P is the path $< x_0, x_1, x_2, \ldots, x_{n-1} >$. A path is called a *hamiltonian path* if its nodes are distinct and span V. A *cycle* is a path of at least three nodes such that the first node is the same as the last node. A cycle is called a *hamiltonian cycle* if its nodes are distinct except for the first node and the last node and if they span V. A graph is called *hamiltonian* if it has a hamiltonian cycle. A graph $G = (V, E)$ is *1–edge hamiltonian* if $G - e$ is hamiltonian for any $e \in E$. A hamiltonian bipartite graph G is 1_p*-hamiltonian* if $G - F$ remains hamiltonian for any $F = \{a, b\}$ with $a \in A$ and $b \in B$ where A and B are the bipartition of G.

For any two positive integers r and s, we use $[r]_s$ to denote $r \pmod{s}$. We use the brick drawing, proposed in (Stojmenovic, 1997), to define the honeycomb rectangular torus. The honeycomb rectangular torus HReT(m, n) is the graph with the vertex set $\{(i, j) \mid 0 \leq i < m, 0 \leq j < n\}$ such that (i, j) and (k, l) are adjacent if they satisfy one of the following conditions:

1. $i = k$ and $j = [l \pm 1]_n$;
2. $j = l$ and $k = [i - 1]_m$ if $i + j$ is even; and
3. $j = l$ and $k = [i + 1]_m$ if $i + j$ is odd.

For example, the graph HReT$(6, 8)$ is shown in Figure 3.1. From the illustration, it is easy to see that HReT(m, n) is a subgraph of the torus $T(m, n)$ (Leighton, 1992). Obviously, any honeycomb rectangular torus is a 3-regular bipartite graph. We set A as $\{(i, j) \mid (i, j) \in V(\text{HReT}(m, n)), \text{ and } i + j \text{ is even}\}$ and set B as $\{(i, j) \mid (i, j) \in V(\text{HReT}(m, n)), \text{ and } i + j \text{ is odd}\}$. Moreover, any honeycomb rectangular torus is vertex transitive. The recursive structure of HReT(m, n) can easily be observed by inserting pair of rows and/or pair of columns.

Since the honeycomb rectangular torus is a bipartite graph, any spanning cycle of it contains the same number of vertices in each part. We will prove that any

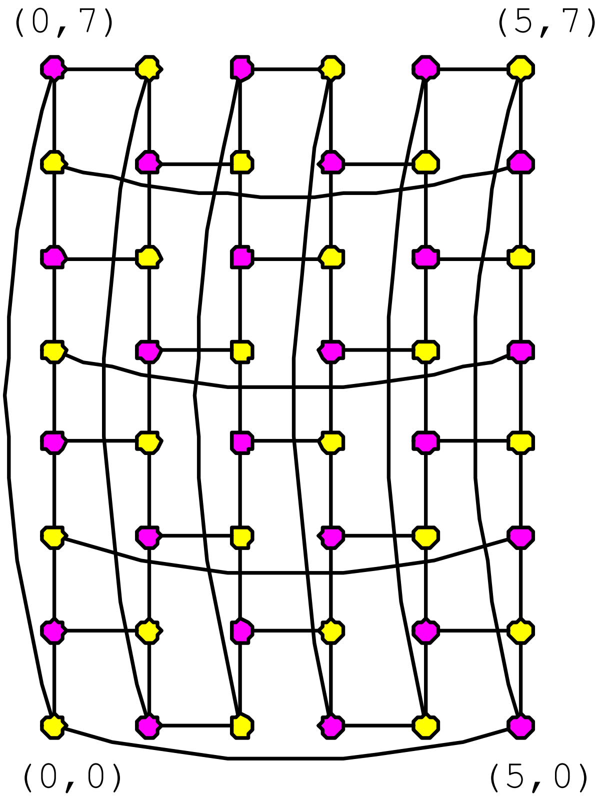


Figure 3.1: The graph HReT$(6,8)$

HReT(m,n) is 1-edge hamiltonian. Moreover, HReT(m,n) is 1_p-hamiltonian if and only if $n > 4$ or $m = 2$.

To discuss the 1_p-hamiltonian property of HReT(m,n), let $F = \{a,b\}$ with $a \in A$ and $b \in B$. We may assume that $(0,0) \in F$ because HReT(m,n) is vertex transitive. For this reason, we use $\mathcal{F}(m,n)$ to denote $\{F \mid F = \{(0,0),(x,y)\} \mid (x,y) \in B\}$. We use (x,y) to denote the unique element in $F - \{(0,0)\}$. By the assumption, $x+y$ is odd. We use $P(i,j,k)$ to denote the path $\langle (i,j),(i,[j+1]_n)),(i,[j+2]_n)),\ldots,(i,k)\rangle$ and use $Q(i,k,j)$ to denote the path $P^{-1}(i,j,k)$.

We will prove that the honeycomb rectangular torus HReT(m,n) is hamiltonian. Moreover, any HReT(m,n) remains hamiltonian when any edge is faulty. The honeycomb rectangular torus we proposed is a bipartite graph with bipartition A and B. Thus, any cycle of it contains the same number of vertices in each part. For this observation, we will prove that any HReT$(m,n) - F$, with $n > 4$ or $m = 2$, remains hamiltonian for any $F = \{a,b\}$ with $a \in A$ and $b \in B$.

3.2 A Recursive Property

In this section, we use F' to denote a subset of $V(\text{HReT}(m,n)) \cup E(\text{HReT}(m,n))$. We will present a recursive algorithm to obtain hamiltonian cycle of HReT$(m,n) - F'$.

Assume that $0 \le i < m$. We define a function from the vertex set of HReT(m, n) into the vertex set of HReT$(m+2, n)$ by assigning $f_i((k,l)) = (k,l)$ if $k \le i$ and $f_i((k,l)) = (k+2,l)$ if otherwise. We define $f_i(F')$ to be the set

$$\begin{aligned} & \{f_i(k,l) \mid (k,l) \in V(HReT(m,n)) \cap F'\} \\ \cup \; & \{(f_i(k,l), f_i(k',l')) \mid ((k,l),(k',l')) \in E(HReT(m,n)) \cap F' \; with \; \{k,k'\} \neq \{i,[i+1]_m\}\} \\ \cup \; & \{((i,l),(i+1,l)) \mid ((i,l),([i+1]_m,l)) \in E(HReT(m,n)) \cap F'\}. \end{aligned}$$

Let H be a hamiltonian cycle of HReT$(m,n) - F'$ such that there are some edges of H joining vertices of column i to vertices of column $[i+1]_m$; i.e., $((i,j),([i+1]_m,j)) \in E(H)$ for some j. Now, we construct a hamiltonian cycle $f_i(H)$ of HReT$(m+2,n) - f_i(F')$ as follows:

Let $0 \le k_0 < k_1 < \ldots < k_{t-1} \le n-1$ be the indices such that $((i,k_j),([i+1]_m,k_j))$ is an edge of H. Let $\bar{H}_i$ be the image of $H - \{(i,j),([i+1]_m,j)) \mid 0 \le j < n\}$ under f_i. For $0 \le j < t$, we set Q_j as the path

$$\begin{aligned} & \langle (i,k_j), ([i+1]_{m+2},k_j) \overset{P([i+1]_{m+2},k_j,[k_{[j+1]_t}-1]_n)}{\longrightarrow} ([i+1]_{m+2},[k_{[j+1]_t}-1]_n), \\ & ([i+2]_{m+2},[k_{[j+1]_t}-1]_n) \overset{Q([i+2]_{m+2},[k_{[j+1]_t}-1]_n,k_j)}{\longrightarrow} ([i+2]_{m+2},k_j), ([i+3]_{m+2},k_j) \rangle. \end{aligned}$$

Obviously, Q_j is a path joining (i,k_j) and $([i+3]_{m+2},k_j)$ for $0 \le j < t$. It is easy to see that edges of $\bar{H}_i$ together with edges of Q_j, with $0 \le j < t$, form a hamiltonian

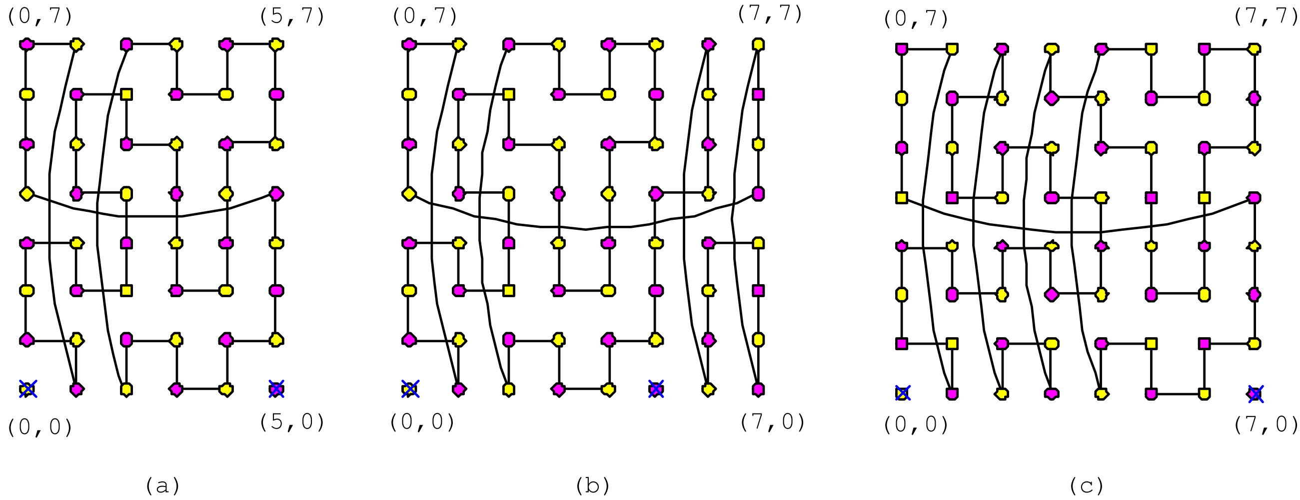


Figure 3.2: (a) a hamiltonian cycle H in HReT$(6,8) - \{(0,0),(5,0)\}$, (b) $f_5(H)$, and (c) $f_1(H)$

cycle of HReT$(m+2,n) - f_i(F')$. We denote this cycle as $f_i(H)$. For example, a hamiltonian cycle H of HReT$(6,8) - \{(0,0),(5,0)\}$ is shown in Figure 3.2(a). The corresponding $f_5(H)$ and $f_1(H)$ are shown in Figures 3.2(b) and 3.2(c). We have following lemmas.

Lemma 1 *Assume that* $0 \leq i < m$. *Let* H *be a hamiltonian cycle of HReT*$(m,n) - F'$ *such that there are some edges of* H *joining vertices of column* i *to vertices of column* $[i+1]_m$. *Then,* $f_i(H)$ *is a hamiltonian cycle of HReT*$(m+2,n) - f_i(F')$. *Moreover,* $f_i(H)$ *contains some edges joining column* t *to column* $[t+1]_{m+2}$ *for any* t *in* $\{i, [i+1]_{m+2}, [i+2]_{m+2}\}$.

Lemma 2 *(1) Suppose that H is a hamiltonian cycle of HReT$(2,n) - F'$ such that H contains some edges in $\{((0,j),(1,j)) \mid j$ is odd$\}$. Then $f_0(H)$ is a hamiltonian cycle of HReT$(4,n) - f_0(F')$. Moreover, $f_0(H)$ contains some edges joining column t to column $t+1$ for any t in $\{0,1,2\}$. (2) Suppose that H is a hamiltonian cycle of HReT$(2,n) - F'$ such that H contains some edges in $\{((0,j),(1,j)) \mid j$ is even$\}$. Then $f_1(H)$ is a hamiltonian cycle of HReT$(4,n) - f_1(F')$. Moreover, $f_1(H)$ contains some edges joining column t to column $t+1$ for any t in $\{1,2,3\}$.*

We say a hamiltonian cycle of HReT$(2,n) - F'$ is *regular* if H contains some edges in $\{((0,j),(1,j)) \mid j$ is odd$\}$ and some edges in $\{((0,j),(1,j)) \mid j$ is even$\}$. Assume that $m \geq 4$. A hamiltonian cycle H of HReT$(m,n) - F'$ is *regular* if H contains some edges joining column i to column $[i+1]_m$ for $0 \leq i < m$. The following lemma is derived from the above two lemmas.

Lemma 3 *Suppose that H is a regular hamiltonian cycle for HReT$(m,n) - F'$. Then $f_i(H)$ is a regular hamiltonian cycle of HReT$(m+2,n) - f_i(F')$ for every $0 \leq i < m$.*

3.3 Hamiltonian Properties of HReT$(2, n)$

Obviously, $\langle (0,0),(1,0),(1,1),(0,1),(0,2),\ldots,(0,n-2),(1,n-2),(1,n-1),(0,n-1),(0,0)\rangle$ and $\langle (0,0) \overset{P(0,0,n-1)}{\longrightarrow} (0,n-1),(1,n-1) \overset{Q(1,n-1,0)}{\longrightarrow} (1,0),(0,0)\rangle$ are regular hamiltonian cycles of HReT$(2,n)$. With these two hamiltonian cycles and the symmetric property of HReT$(2,n)$, HReT$(2,n)$ is 1-edge hamiltonian.

Now, we discuss the 1_p-hamiltonian property of HReT$(2,n)$. Assume that $F \in \mathcal{F}(2,n)$ and (x,y) be the unique element in $F - \{(0,0)\}$.

Suppose that $x = 0$. Then

$$\langle (0,1),(0,2),(1,2),(1,3),\ldots,(0,y-1),(1,y-1),(1,y),(1,y+1),(0,y+1),\ldots,$$
$$(0,n-3),(1,n-3),(1,n-2),(0,n-2),(0,n-1),(1,n-1),(1,0),(1,1),(0,1)\rangle$$

forms a hamiltonian cycle of HReT$(2,n) - F$.

Suppose that $x = 1$. Then

$$\langle (0,1),(0,2),(1,2),(1,3),\ldots,(1,y-1),(0,y-1),(0,y),(0,y+1),(1,y+1),\ldots,$$
$$(0,n-3),(1,n-3),(1,n-2),(0,n-2),(0,n-1),(1,n-1),(1,0),(1,1),(0,1)\rangle$$

forms a hamiltonian cycle of HReT$(2,n) - F$.

Lemma 4 *HReT$(2,n)$ is 1-edge hamiltonian and 1_p-hamiltonian. Moreover, there exists a regular hamiltonian cycle in HReT$(2,n) - e$ for any $e \in E($HReT$(2,n))$.*

Furthermore, there exists a regular hamiltonian cycle in HReT$(2, n) - F$ *for any* $F \in \mathcal{F}(2, n)$ *with* $F \neq \{(0,0), (1,0)\}$.

3.3.1 1_p-hamiltonian property of HReT$(4, n)$

We first consider the case HReT$(4,4)$. Suppose that $F = \{(0,0), (1,0)\}$. Obviously, $deg_{G-F}(v) = 2$ if $v \in \{(0,1), (0,3), (1,1), (1,3)\}$. For this reason, any hamiltonian cycle of HReT$(4,4) - F$ must include the following edge set:

$$\{((0,1),(0,2)),((0,2),(0,3)),((0,3),(1,3)),((1,3),(1,2)),((1,2),(1,1)),((1,1),(0,1))\}.$$

However, this edge set induces a cycle of length 6. Thus, HReT$(4,4) - F$ is not hamiltonian.

In the following, we will prove that every HReT$(4, n)$ with $n \geq 6$ is 1_p-hamiltonian. Assume t is an integer with $0 \leq t < (\frac{n}{4} - 1)$. For $0 \leq i \leq 2t$, let D_i denote the path $\langle (3, 2i), (3, 2i+1), (2, 2i+1), (2, 2i+2), (1, 2i+2), (1, 2i+3), (0, 2i+3), (0, 2i+4) \rangle$.

We set R_t as the path

$$\langle (3,0) \xrightarrow{D_0} (0,4), (3,4) \xrightarrow{D_2} (0,8), (3,8) \ldots \xrightarrow{D_{2t-2}} (0,4t) \rangle$$

and set S_t as the path

$$\langle (3,2) \xrightarrow{D_1} (0,6), (3,6) \xrightarrow{D_3} (0,10), (3,10) \ldots \xrightarrow{D_{2t-1}} (0,4t+2) \rangle.$$

Let $F \in \mathcal{F}(4,n)$ and (x,y) be the unique element in $F - \{(0,0)\}$.

Case 1: $x = 0$. By Lemma 4, there exists a hamiltonian cycle H of $\mathrm{HReT}(2,n) - F$. By Lemma 2, $f_0(H)$ is a regular hamiltonian cycle of $\mathrm{HReT}(4,n) - F$.

Case 2: $x = 1$. Assume that $(x,y) \neq (1,0)$. By Lemma 4, there exists a regular hamiltonian cycle H of $\mathrm{HReT}(2,n) - F$. By Lemma 2, $f_1(H)$ is a regular hamiltonian cycle of $\mathrm{HReT}(4,n) - F$. Suppose that $(x,y) = (1,0)$. It can be checked that

$$\langle (0,1),(0,2),(0,3),(1,3) \overset{P(1,3,n-1)}{\longrightarrow} (1,n-1),(0,n-1) \overset{Q(0,n-1,4)}{\longrightarrow} (0,4),$$
$$(3,4) \overset{P(3,4,3)}{\longrightarrow} (3,3),(2,3) \overset{P(2,3,2)}{\longrightarrow} (2,2),(1,2),(1,1),(0,1)\rangle$$

forms a regular hamiltonian cycle of $\mathrm{HReT}(4,n) - F$. See Figure 3.3(a) for illustration.

Case 3: $x = 2$. By the symmetric property of $\mathrm{HReT}(4,n)$, we may assume that $1 \leq y \leq \frac{n}{2}$. Since $x + y$ is odd, y is odd.

Subcase 3.1: $y = 1$. It can be checked that

$$\langle (0,1),(0,2),(3,2) \overset{Q(3,2,3)}{\longrightarrow} (3,3),(2,3),(2,2),(1,2),(1,3),(0,3) \overset{P(0,3,n-1)}{\longrightarrow} (0,n-1),$$
$$(1,n-1) \overset{Q(1,n-1,4)}{\longrightarrow} (1,4),(2,4) \overset{P(2,4,0)}{\longrightarrow} (2,0),(1,0),(1,1),(0,1)\rangle$$

forms a regular hamiltonian cycle of $\mathrm{HReT}(4,n) - F$. See Figure 3.3(b) for illustration.

Subcase 3.2: $y = 4t + 1$ for some positive integer t. Then the path

$$\langle(3,0) \xrightarrow{R_t} (0,4t),(3,4t)(3,4t+1),(3,4t+2),(0,4t+2) \xrightarrow{S_t^{-1}} (3,2),(0,2),$$

$$(0,1),(1,1),(1,0),(2,0) \overset{Q(2,0,4t+4)}{\longrightarrow} (2,4t+4),(1,4t+4) \overset{P(1,4t+4,n-1)}{\longrightarrow} (1,n-1),$$

$$(0,n-1) \overset{Q(0,n-1,4t+3)}{\longrightarrow} (0,4t+3),(1,4t+3),(1,4t+2),(2,4t+2),$$

$$(2,4t+3),(3,4t+3) \overset{P(3,4t+3,0)}{\longrightarrow} (3,0)\rangle$$

forms a hamiltonian cycle of $\mathrm{HReT}(4,n) - F$. See Figure 3.3(c) for illustration.

Subcase 3.3: $y = 4t + 3$ for some nonnegative integer t. Then the path

$$\langle(3,0) \xrightarrow{R_t} (0,4t) \xrightarrow{D_{2t}} (0,4t+4) \overset{P(0,4t+4,n-1)}{\longrightarrow} (0,n-1),$$

$$(1,n-1) \overset{Q(1,n-1,4t+4)}{\longrightarrow} (1,4t+4),(2,4t+4) \overset{P(2,4t+4,0)}{\longrightarrow} (2,0),(1,0),(1,1),$$

$$(0,1),(0,2),(3,2) \xrightarrow{S_t} (0,4t+2),(3,4t+2) \overset{P(3,4t+2,0)}{\longrightarrow} (3,0)\rangle$$

forms a hamiltonian cycle of $\mathrm{HReT}(4,n) - F$. See Figure 3.3(d) for illustration.

Case 4: $x = 3$. Assume that $(x,y) \neq (3,0)$. By Lemma 4, there exists a hamiltonian cycle H of $\mathrm{HReT}(2,n) - \{(0,0),(1,y)\}$. By Lemma 2, $f_0(H)$ is a regular hamiltonian cycle of $\mathrm{HReT}(4,n) - F$. Assume that $(x,y) = (3,0)$. Suppose that $n \geq 8$. It can be checked that

$$\langle(0,1),(0,2),(0,3),(1,3),(1,2),(2,2),(2,3),(2,4),(1,4) \overset{P(1,4,n-2)}{\longrightarrow} (1,n-2),$$

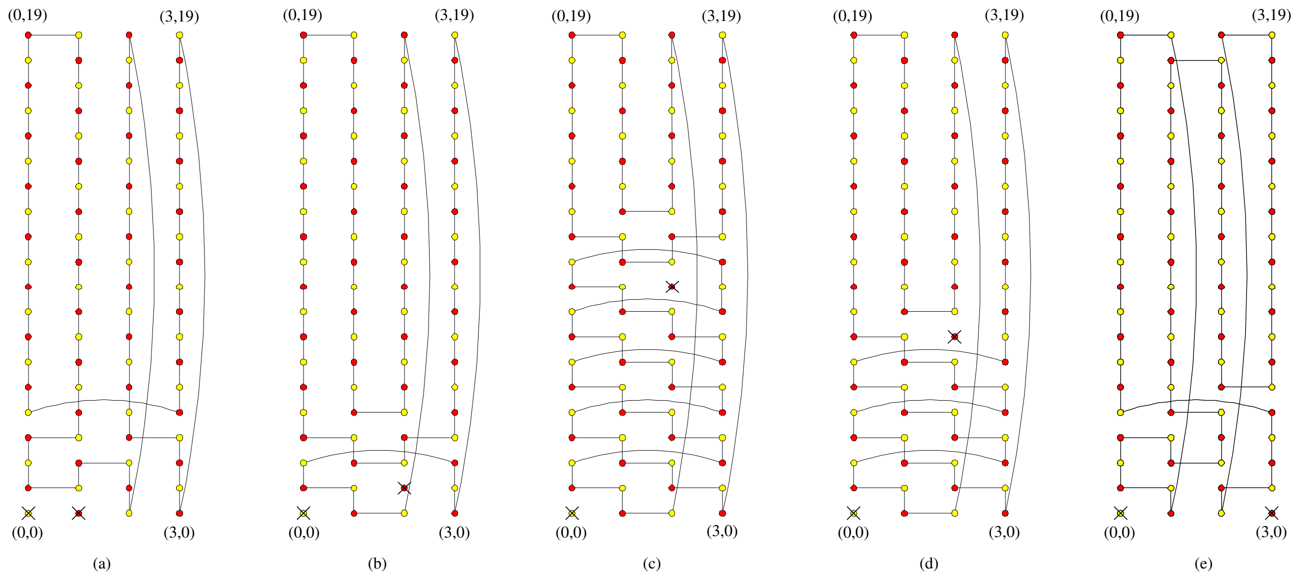


Figure 3.3: (a) a hamiltonian cycle H in $\mathrm{HReT}(4,20) - \{(0,0),(1,0)\}$, (b) a hamiltonian cycle H in $\mathrm{HReT}(4,20) - \{(0,0),(2,1)\}$, (c) a hamiltonian cycle H in $\mathrm{HReT}(4,20) - \{(0,0),(2,9)\}$, (d) a hamiltonian cycle H in $\mathrm{HReT}(4,20) - \{(0,0),(2,7)\}$, and (e) a hamiltonian cycle H in $\mathrm{HReT}(4,20) - \{(0,0),(3,0)\}$.

$$(2,n-2) \xrightarrow{Q(2,n-2,5)} (2,5),(3,5) \xrightarrow{P(3,5,n-1)} (3,n-1),(2,n-1),(2,0),(2,1),$$

$$(3,1) \xrightarrow{P(3,1,4)} (3,4),(0,4) \xrightarrow{P(0,4,n-1)} (0,n-1),(1,n-1),(1,0),(1,1)(0,1)\rangle$$

forms a regular hamiltonian cycle of $\mathrm{HReT}(4,n) - F$. See Figure 3.3(e) for illustration.

Hence, we have the following lemma.

Lemma 5 *(1) HReT$(4,n)$ is 1_p-hamiltonian if and only if $n \geq 6$.*

(2) Suppose that $n \geq 6$. There exists a regular hamiltonian cycle in HReT$(m,n) - F$

for any $F \in \mathcal{F}(4, n)$ *except the case that* $F = \{(0,0),(3,0)\}$ *and* $n = 6$.

3.4 Hamiltonian Properties of HReT(m, n)

Theorem 1 *(1) Any rectangular honeycomb torus* $HReT(m, n)$ *is 1-edge hamiltonian.*

(2) $HReT(m, n)$ *is* 1_p*-hamiltonian if and only if either* $n \geq 6$ *or* $m = 2$.

(3) Assume that $m \geq 4$, $n \geq 6$. *There exists a regular hamiltonian cycle in* $HReT(m, n) - F$ *for any* $F \in \mathcal{F}(m, n)$ *except the case that* $F = \{(0,0),(m-1,0)\}$ *and* $n = 6$.

Proof. With Lemma 4, there exists a regular hamiltonian cycle in HReT$(2, n) - e$ for any $e \in E(\text{HReT}(2, n))$. Recursively applying Lemma 3, any rectangular honeycomb torus HReT(m, n) is 1-edge hamiltonian.

Now, we discuss the 1_p-hamiltonian property of HReT(m, n). Let $F \in \mathcal{F}(m, n)$ and (x, y) be the unique element in $F - \{(0,0)\}$. By Lemma 4, HReT$(2, n)$ is 1_p-hamiltonian.

Now, we consider the case $n = 4$. Suppose that $F = \{(0,0),(1,0)\}$. Obviously, $deg_{G-F}(v) = 2$ if $v \in \{(0,1),(0,3),(1,1),(1,3)\}$. Therefore, any hamiltonian cycle of $\mathrm{HReT}(m,n) - F$ must include the following edge set:

$$\{((0,1),(0,2)),((0,2),(0,3)),((0,3),(1,3)),((1,3),(1,2)),((1,2),(1,1)),((1,1),(0,1))\}.$$

However, this edge set induces a cycle of length 6. Thus, $\mathrm{HReT}(m,n) - F$ is not hamiltonian. Hence, $\mathrm{HReT}(m,n)$ is not 1_p-hamiltonian if $m \geq 4$ and $n = 4$.

Now, we prove that $\mathrm{HReT}(m,n)$ is 1_p-hamiltonian if $n \geq 6$. We prove the statement by induction on m. With Lemma 5, our theorem holds for $m = 4$. Hence, we assume that the theorem holds for $\mathrm{HReT}(m',n)$ when m' is any even integer with $4 \leq m' < m$. Now, we consider the case that $m \geq 6$.

We first consider the case that $n \geq 8$. Suppose that $x < m-2$. By induction, there exists a regular hamiltonian cycle H of $\mathrm{HReT}(m-2,n) - F$. By Lemma 2, $f_{m-1}(H)$ is a regular hamiltonian cycle of $\mathrm{HReT}(m,n) - F$. Suppose that $x \geq m-2$. By induction, there exists a regular hamiltonian cycle H of $\mathrm{HReT}(m-2,n) - \{(0,0),(x-2,y)\}$. By Lemma 2, $f_0(H)$ is a regular hamiltonian cycle of $\mathrm{HReT}(m,n) - F$. Hence, the theorem holds for $n \geq 8$.

Now, we consider the case that $n = 6$. Suppose that (x,y) is neither $(m-3,0)$ nor $(m-1,0)$. By induction, there exists a regular hamiltonian cycle H of $\mathrm{HReT}(m-2,n) - F$. By Lemma 2, $f_{m-1}(H)$ is a regular hamiltonian cycle of $\mathrm{HReT}(m,n) - F$. Suppose that $(x,y) = (m-3,0)$. By induction, there exists a regular hamiltonian cycle H of HReT$(m-2,n)-\{(0,0),(m-5,0)\}$. By Lemma 2, $f_0(H)$ is a regular hamiltonian cycle of HReT$(m,n)-F$. Suppose that $(x,y)=(m-1,0)$. By induction, there exists a hamiltonian cycle H of HReT$(m-2,n)-\{(0,0),(m-3,0)\}$. The hamiltonian cycle must contain some edges joining column i to column $i+1$ for some i with $0\leq i\leq m-2$. By Lemma 2, $f_i(H)$ is a hamiltonian cycle of HReT$(m,n)-F$.

The theorem is proved. $\square$

Chapter 4

Hamiltonian Properties of GHT Network

After basic definitions in Section 4.1, we will prove that HReT network and honeycomb torus torus can be isomorphic to the GHT network in Section 4.2. In Section 4.3, we will prove if m and k are positive integers and $(m-k)$ is an even number, then GHT$(m, 2k, k)$ is hamiltonian (this network configuration is basically proposed for service or secondary tunnels).

4.1 Definitions

The denitions related to HReT(m, n) are shown in Section 4.1. Now, assume that m and n are positive integers where n is even. The *honeycomb rhombic torus* HRoT(m, n) is the graph with the node set $\{(i, j) \mid 0 \leq i < m, 0 \leq j - i < n\}$ such that (i, j) and (k, l) are adjacent if they satisfy one of the following conditions:

1. $i = k$ and $j = l \pm 1 \ (\mathbf{mod}\ n)$;

2. $j = l$ and $k = i - 1$ if $i + j$ is even; and

3. $i = 0$, $k = m - 1$, and $l = j + m$ if j is even.

Assume that n is a positive integer. The *honeycomb hexagonal mesh* $HM(n)$ is the graph with the node set $\{(x_1, x_2, x_3) \mid -n + 1 \leq x_1, x_2, x_3 \leq n$ and $1 \leq x_1 + x_2 + x_3 \leq 2\}$. Two nodes (x_1^1, x_2^1, x_3^1) and (x_1^2, x_2^2, x_3^2) are adjacent if and only $|x_1^1 - x_1^2| + |x_2^1 - x_2^2| + |x_3^1 - x_3^2| = 1$. The *honeycomb hexagonal torus* $HT(n)$ is the graph with the same node set as $HM(n)$. The edge set is the union of $E(HM(n))$ and the wraparound edge set

$$\begin{aligned} & \{((i, n - i + 1, 1 - n), (i - n, 1 - i, n)) \mid 1 \leq i \leq n\} \\ \cup \ & \{((1 - n, i, n - i + 1), (n, i - n, 1 - i)) \mid 1 \leq i \leq n\} \\ \cup \ & \{((i, 1 - n, n - i + 1), (i - n, n, 1 - i)) \mid 1 \leq i \leq n\}. \end{aligned}$$

Assume that m and n are positive integers where n is even. Let d be any integer such that $(m - d)$ is an even number. The *generalized honeycomb rectangular torus* GHT(m, n, d) is the graph with the node set $\{(i, j) \mid 0 \leq i < m, 0 \leq j < n\}$ such that (i, j) and (k, l) are adjacent if they satisfy one of the following conditions:

1. $i = k$ and $j = l \pm 1 \ (\mathbf{mod}\ n)$;

2. $j = l$ and $k = i - 1$ if $i + j$ is even; and

3. $i = 0$, $k = m - 1$, and $l = j + d \ (\mathbf{mod}\ n)$ if j is even.

See Figure 4.1 for various honeycomb tori. Obviously, any GHT(m, n, d) is a 3-regular bipartite graph. We can label those nodes (i, j) white when $i + j$ is even or black if otherwise.

4.2 Isomorphisms

If two graphs have a one-to-one mapping,this relationship is called isomorphism. We can easily find that HReT(m, n) is isomorphic to GHT$(m, n, 0)$ and HRoT(m, n) is isomorphic to GHT$(m, n, m \ (\mathbf{mod}\ n))$. With the following theorem, the honeycomb hexagonal torus (or simply: honeycomb torus (Stojmenovic, 1997; Megson, Yang & Liu, 1999, Megson, Liu & Yang, 1999) HT(n) is isomorphic to GHT$(n, 6n, 3n)$.

Theorem 2 *HT*(n) *is isomorphic to GHT*$(n, 6n, 3n)$.

Proof. Let h be the function from the node set of HT(n) into the node set of GHT$(n, 6n, 3n)$ by setting $h(x_1, x_2, x_3) = (x_3, x_1 - x_2 + 2n)$ if $0 \leq x_3 < n$, $h(x_1, x_2, x_3) = (0, x_1 - x_2 + 5n \ (\mathbf{mod}\ 6n))$ if $x_3 = n$, and $h(x_1, x_2, x_3) = (x_3 + n, x_1 - x_2 + 5n \ (\mathbf{mod}\ 6n))$ if otherwise.

For any $1 - n \leq c \leq n$, we use X_c to denote the set of those nodes (x_1, x_2, x_3) in HT(n) with $x_3 = c$. We use Y_c to denote the set of nodes (i, j) in GHT$(n, 6n, 3n)$

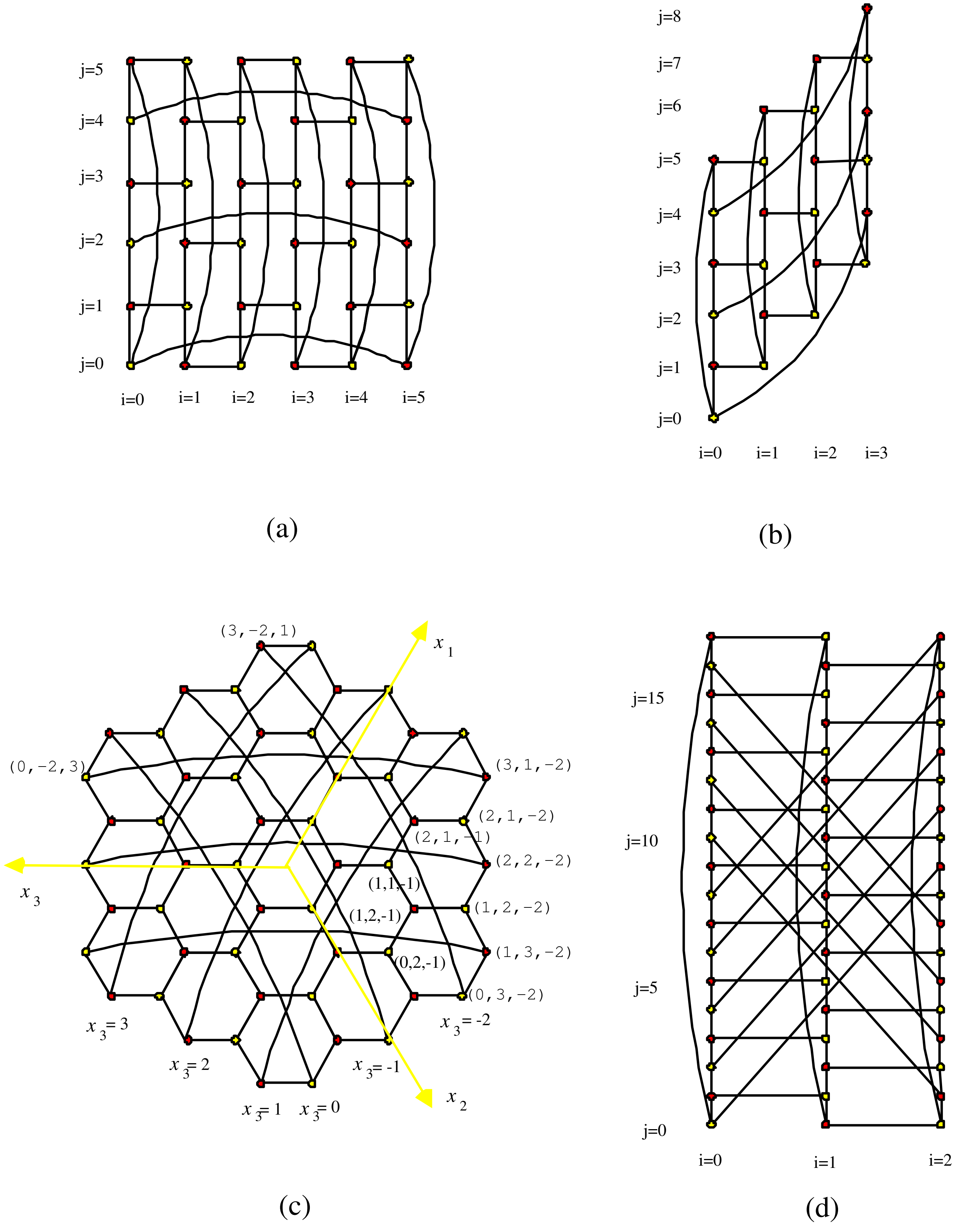


Figure 4.1: (a) HReT(6, 6), (b) HRoT(4, 6), (c) HT(3), and (d) GHT(3, 18, 9)

where (1) $i = c + n$ and $j \in \{k \mid 4n - c - 3 < k < 6n\} \cup \{k \mid 0 \leq k < n + c\}$ if $c < 0$, (2) $i = 0$ and $j \in \{1 \leq j < 4n\}$ if $c = 0$, (3) $i = c$ and $\{j \mid c \leq j \leq 4n - c\}$ if $0 < c < n$, and (4) $i = 0$ and $j \in \{k \mid 4n \leq k < 6n\} \cup \{0\}$ if $c = n$. Let h_c denote the function of h induced by X_c. It is easy to check that h_c is a one-to-one function from X_c onto Y_c. Thus, h is one-to-one and onto.

To prove h is an isomorphism, we need to check that h preserves the adjacency. Suppose that $e = ((x_1, x_2, x_3), (x'_1, x'_2, x'_3))$ be an edge of HT(n). Without loss of generality, we assume that $x_1 + x_2 + x_3 = 2$ and $x'_1 + x'_2 + x'_3 = 1$.

Suppose that e is an edge of HM(n). Then either $x_3 = x'_3$ or $x_3 - x'_3 = \pm 1$.

Case 1: $x_3 = x'_3$. Obviously, either $(x'_1, x'_2, x'_3) = (x_1 - 1, x_2, x_3)$ or $(x'_1, x'_2, x'_3) = (x_1, x_2 - 1, x_3)$ holds.

Suppose that $0 \leq x_3 < n$. Then $h(x_1, x_2, x_3) = (x_3, x_1 - x_2 + 2n)$. Moreover, $h(x'_1, x'_2, x'_3) = (x_3, x_1 - x_2 - 1 + 2n)$ if $(x'_1, x'_2, x'_3) = (x_1 - 1, x_2, x_3)$ and $h(x'_1, x'_2, x'_3) = (x_3, x_1 - x_2 + 1 + 2n)$ if $(x'_1, x'_2, x'_3) = (x_1, x_2 - 1, x_3)$. Suppose that $x_3 = n$. Then $h(x_1, x_2, x_3) = (0, x_1 - x_2 + 5n \pmod{6n})$. Moreover, $h(x'_1, x'_2, x'_3) = (x_3, x_1 - x_2 - 1 + 5n \pmod{6n})$ if $(x'_1, x'_2, x'_3) = (x_1 - 1, x_2, x_3)$ and $h(x'_1, x'_2, x'_3) = (x_3, x_1 - x_2 + 1 + 5n \pmod{6n})$ if $(x'_1, x'_2, x'_3) = (x_1, x_2 - 1, x_3)$. Suppose that $x_3 < 0$.

Then $h(x_1, x_2, x_3) = (x_3 + n, x_1 - x_2 + 5n \ (\mathbf{mod}\ 6n))$. Moreover, $h(x_1', x_2', x_3') = (x_3, x_1 - x_2 - 1 + 5n \ (\mathbf{mod}\ 6n))$ if $(x_1', x_2', x_3') = (x_1 - 1, x_2, x_3)$ and $h(x_1', x_2', x_3') = (x_3, x_1 - x_2 + 1 + 5n \ (\mathbf{mod}\ 6n))$ if $(x_1', x_2', x_3') = (x_1, x_2 - 1, x_3)$. Hence, $h(x_1, x_2, x_3)$ and $h(x_1', x_2', x_3')$ are adjacent.

Case 2: $x_3 - x_3' = \pm 1$. Since $x_1 + x_2 + x_3 = 2$ and $x_1' + x_2' + x_3' = 1$, $(x_1', x_2', x_3') = (x_1, x_2, x_3 - 1)$.

Suppose that $1 \leq x_3 < n$. Then $h(x_1, x_2, x_3) = (x_3, x_1 - x_2 + 2n)$ and $h(x_1', x_2', x_3') = (x_3 - 1, x_1 - x_2 + 2n)$. Suppose that $x_3 = 0$. Then $h(x_1, x_2, x_3) = (0, x_1 - x_2 + 2n)$ and $h(x_1', x_2', x_3') = (n - 1, x_1 - x_2 + 5n \ (\mathbf{mod}\ 6n))$. Suppose that $x_3 = n$. Then $h(x_1, x_2, x_3) = (0, x_1 - x_2 + 5n \ (\mathbf{mod}\ 6n))$ and $h(x_1', x_2', x_3') = (n - 1, x_1 - x_2 + 2n)$. Suppose that $2 - n \leq x_3 \leq -1$. Then $h(x_1, x_2, x_3) = (x_3 + n, x_1 - x_2 + 5n \ (\mathbf{mod}\ 6n))$ and $h(x_1', x_2', x_3') = (x_3 + n - 1, x_1 - x_2 + 5n \ (\mathbf{mod}\ 6n))$. Hence, $h(x_1, x_2, x_3)$ and $h(x_1', x_2', x_3')$ are adjacent.

Suppose that e is an wraparound edge of $\mathrm{HM}(n)$. Then, we have the following three cases.

Case 3: $e \in \{((i, n - i + 1, 1 - n), (i - n, 1 - i, n)) \mid 1 \leq i \leq n\}$. Then $(x_1, x_2, x_3) = (i, n - i + 1, 1 - n)$ and $(x_1', x_2', x_3') = (i - n, 1 - i, n)$. Obviously, $h(x_1, x_2, x_3)$

is $(1, 4n + 2i - 1)$ and $h(x'_1, x'_2, x'_3)$ is $(0, 4n + 2i - 1)$). Hence, $h(x_1, x_2, x_3)$ and $h(x'_1, x'_2, x'_3)$ are adjacent.

Case 4: $e \in \{((1-n, i, n-i+1), (n, i-n, 1-i)) \mid 1 \leq i \leq n\}$. Hence $(x_1, x_2, x_3) = (1-n, i, n-i+1)$ and $(x'_1, x'_2, x'_3) = (n, i-n, 1-i)$. Obviously, $h(x_1, x_2, x_3)$ is $(0, 4n)$ if $i = 1$ and $(n-i+1, n-i+1)$ if $1 < i \leq n$. Similarly, $h(x'_1, x'_2, x'_3)$ is $(0, 4n-1)$) if $i = 1$ and $(n-i+1, n-i)$ if $1 < i \leq n$. Thus, $h(x_1, x_2, x_3)$ and $h(x'_1, x'_2, x'_3)$ are adjacent.

Case 5: $e \in \{((i, 1-n, n-i+1), (i-n, n, 1-i)) \mid 1 \leq i \leq n\}$. Thus $(x_1, x_2, x_3) = (i, 1-n, n-i+1)$ and $(x'_1, x'_2, x'_3) = (i-n, n, 1-i)$. Obviously, $h(x_1, x_2, x_3)$ is $(0, 0)$ if $i = 1$ and $(n-i+1, 3n+i-1)$ if $1 < i \leq n$. Similarly, $h(x'_1, x'_2, x'_3)$ is $(0, 1)$) if $i = 1$ and $(n-i+1, 3n+i)$ if $1 < i \leq n$. Again, $h(x_1, x_2, x_3)$ and $h(x'_1, x'_2, x'_3)$ are adjacent.

Thus, the theorem is proved. $\square$

For example, the honeycomb torus shown in Figure 4.1(c) is actually isomorphic to the generalized honeycomb torus shown in Figure 4.1(d).

4.3 Hamiltonian Properties of Some Generalized Honeycomb Tori

It is easy to prove that any honeycomb rectangular torus and any honeycomb rhombic torus are hamiltonian. In (Megson, Yang & Liu, 1999), it is proved that any honeycomb hexagonal torus is hamiltonian. We reprove this result with the following theorem.

Theorem 3 *Any generalized honeycomb torus $GHT(m, 2k, k)$ is hamiltonian.*

Proof. In $\mathrm{GHT}(m, 2k, k)$, let $P(i, j, s)$ denote the path $\langle (i, j), (i, j+1\,(\mathbf{mod}\ 2k)), (i, j+2\,(\mathbf{mod}\ 2k)), \ldots, (i, s)\rangle$ and $Q(i, s, j)$ denote the path $P^{-1}(i, j, s)$.

Assume that m is even. By the definition of $\mathrm{GHT}(m, 2k, k)$, k is even. Thus $k = 2r$ for some positive integer r.

Let R denote the path from $(0, 0)$ to $(m-1, 0)$ defined by:

$$\langle (0,0) \xrightarrow{P(0,0,2r-1)} (0, 2r-1), (1, 2r-1) \xrightarrow{Q(1,2r-1,0)} (1, 0), \ldots,$$

$$(m-3, 2r-1) \xrightarrow{Q(m-3,2r-1,0)} (m-3, 0), (m-2, 0) \xrightarrow{P(m-2,0,2r-1)} (m-2, 2r-1),$$

$$(m-1, 2r-1) \xrightarrow{Q(m-1,2r-1,0)} (m-1, 0)\rangle.$$

Let S denote the path from $(0,2r)$ to $(m-1,2r)$ defined by:

$$\langle(0,2r) \stackrel{P(0,2r,4r-1)}{\longrightarrow} (0,4r-1),(1,4r-1) \stackrel{Q(1,4r-1,2r)}{\longrightarrow} (1,2r),\ldots,$$

$$(m-3,4r-1) \stackrel{Q(m-3,4r-1,2r)}{\longrightarrow} (m-3,2r),(m-2,2r) \stackrel{P(m-2,2r,4r-1)}{\longrightarrow} (m-2,4r-1),$$

$$(m-1,4r-1) \stackrel{Q(m-1,4r-1,2r)}{\longrightarrow} (m-1,2r)\rangle.$$

Obviously, $\langle(0,0) \stackrel{R}{\longrightarrow} (m-1,0),(0,2r) \stackrel{S}{\longrightarrow} (m-1,2r)),(0,0)\rangle$ forms a hamiltonian cycle for GHT$(m,2k,k)$. See Figure 4.2(a) for illustration.

Assume that m is odd. By the definition of GHT$(m,2k,k)$, k is odd. Suppose that $m=1$. Obviously, $\langle(0,0), \stackrel{P(0,0,2k-1)}{\longrightarrow} (0,2k-1),(0,0)\rangle$ forms a hamiltonian cycle for GHT$(m,2k,k)$ Thus, we assume that $m>1$ and $k=2r+1$ for some nonnegative integer r.

Let X denote the path from $(m-1,2r+1)$ to $(1,2r+1)$ defined by:

$$\langle(m-1,2r+1) \stackrel{Q(m-1,2r+1,0)}{\longrightarrow} (m-1,0),(m-2,0) \stackrel{P(m-2,0,2r+1)}{\longrightarrow} (m-2,2r+1),\ldots,$$

$$(3,0) \stackrel{Q(3,0,2r+1)}{\longrightarrow} (3,2r+1),(2,2r+1) \stackrel{Q(2,2r+1,0)}{\longrightarrow} (2,0),$$

$$(1,0) \stackrel{P(1,0,2r+1)}{\longrightarrow} (1,2r+1)\rangle.$$

Let Y denote the path from $(0,2r+2)$ to $(m-1,4r+1)$ defined by:

$$\langle(0,2r+2) \stackrel{P(0,2r+2,4r+1)}{\longrightarrow} (0,4r+1),(1,4r+1) \stackrel{Q(1,4r+1,2r+2)}{\longrightarrow} (1,2r+2),\ldots,$$

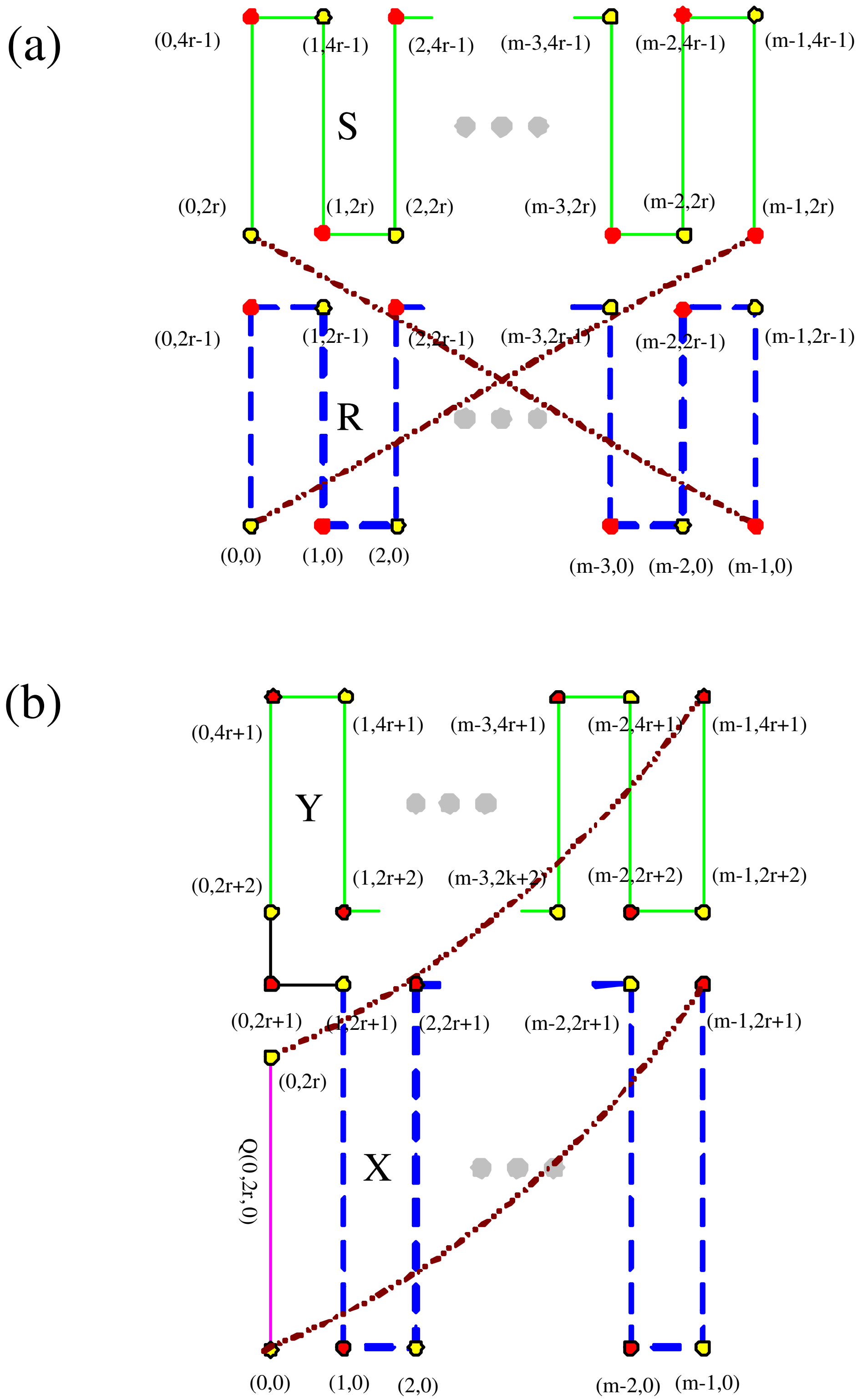


Figure 4.2: Illustrations for Theorem 3.

$$(m-3, 2r+2) \overset{P(m-3,2r+2,4r+1)}{\longrightarrow} (m-3, 4r+1),$$

$$(m-2, 4r+1) \overset{Q(m-2,4r+1,2r+2)}{\longrightarrow} (m-2, 2r+2),$$

$$(m-1, 2r+2) \overset{P(m-1,2r+2,4r+1}{\longrightarrow} (m-1, 4r+1)\rangle.$$

Obviously,

$$\langle(0,0), (m-1, 2r+1) \xrightarrow{X} (1, 2r+1), (0, 2r+1),$$

$$(0, 2r+2) \xrightarrow{Y} (m-1, 4r+1)), (0, 2r) \overset{Q(0,2r,0)}{\longrightarrow} (0,0)\rangle$$

forms a hamiltonian cycle for GHT$(m, 2k, k)$. See Figure 4.2(b) for illustration.

The theorem is proved. □

By Theorems 2 and 3, any honeycomb torus HT(n) is hamiltonian. Moreover, GHT(m,2k,k) can be 1–edge hamiltonian, since nodes can be transistive and the broken edge can be located not on the hamiltonian cycle shown in Figure 4.2.

Chapter 5

Establishing Network Configurations for Tunnels

5.1 Physical Surveillance and Control Concerns for Tunnels

5.1.1 Review the development and hazard prevention of the modern tunnel

Tunnel is an underground or underwater passageway. With the rise of commerce and industry many canal and railway tunnels were built through mountains and under rivers, shortening the travel time for freight and passengers. As the urban population grew, a need for subway tunnels arose. One major consideration in the expanding use of tunnels is that they do not disturb the web of plant, animal, and human life on the surface of the earth (Encyclopedia Americana Online, March 2003). Quality or environment protection is becoming an important concern for deciding whether a tunnel is built; similar quality related environment considerations should

Table 5.1: Longest Rail Tunnels in the World

Name	Location	Length (km)	Completion Date	Remarks
Sei-kan	Tsugaru Strait	53.85	1988	
Channel	English Channel	50.45	1994	34 people trapped in a fire accident, Nov. 18, 1996. Diamantidis et al, 2000, www.apt -p.com /aptdiaster.htm
Daishimizu	Japan	22.22	1982	
Simplon -- II	Switzerland -- Italy	19.82	1922	
Simplon -- I	Switzerland -- Italy	19.80	1906	
Vereina	Switzerland	19.06	1999	
Shinkanmon	Japan	18.71	1975	
Appennino	Italy	18.51	1934	
Qunling I & II	China	18.46	2001	
Rokko	Japan	16.22	1972	
Furka Base	Switzerland	15.44	1982	
Haruna	Japan	15.30	1982	
Severomuyskiy	Russia	15.30	2001	
Gorigamine	Japan	15.18	1997	
Monte Santomacro	Italy	15.04	1987	
St Gotthard	Switzerland	15.00	1882	
Source: Encyclopedia Americana Online, March, 2003				

be well designed, maintained and continuously controlled in the tunnel, especially for lengthy tunnels. (Vuilleumier et al, 2002, p.155–156)

The 53.9–km–long Seikan Tunnel is the longest rail tunnel as well as the longest tunnel in the world. It was completed in 1988, and links the northern island of Hokkaido with Honshu. Rivaling it in length is the 50.5–km–long Channel Tun-

Table 5.2: Longest Land Road Tunnels in the World

Name	Location	Length (km)	Completion Date	Remarks
Laerdal	Norway	24.51	2000	
St. Gotthard	Switzerland	16.92	1980	Truck crash killed 8+ people, Oct. 24, 2001, Vuilleumier et al, 2002; www .structurae .de
Arlberg	Austria	13.97	1978	
Frejus	France -- Italy	12.90	1980	
Mont -- Blanc	France -- Italy	11.61	1965	Truck carrying flour and margarine caught fire and killed 35+ people, Mar. 24 – 26, 1999, Vuilleumier et al, 2002; www .structurae .de
Gudvanga	Norway	11.43	1991	
Folgefonn	Norway	11.13	2001	
Kan–etsu(Southbound)	Japan	11.06	1991	
Kan–etsu(Notthbound)	Japan	10.93	1985	
Gran Sasso d' Italia (east direction)	Italy	10.18	1984	
Gran Sasso d' Italia (west direction)	Italy	10.17	1995	
Source: Encyclopedia Americana Online, March, 2003				

nel, which was bored under the English Channel between Folkestone, England, and Sangatte, France. It was completed in 1994, see Table 5.1. The subway tunnel is also a type of the rail tunnel. Due to the need of urbanization, it started from the beginning of the London Underground system in the 1860s.

Notable long land road tunnels were generally built in the Alps region; include

Table 5.3: Longest Underwater Road Tunnels in the World

Name	Location	Length (km)	Completion Date	Remarks
Tokyo Aqua	Tokyo Bay, Japan	9.58	1997	
Bomlafjord	Norway	7.92	2000	
Hvalfjardargong	Iceland	5.77	1998	
Hitra	Norway	5.65	1994	
Vagatunnilin	Faeroes	4.94	2002	
Drogden	Denmark	3.52	2000	
Kanmon	Kanmon Strait, Japan	3.46	1958	
Burnley	Australia	3.40	2000	
Mersey Queensway	England	3.23	1934	
Musko	Sweden	3.00	1964	
Source: Encyclopedia Americana Online, March, 2003				

three historically longest road tunnels: the 11.6–km– long Mont Blanc Tunnel, completed in 1965 between France and Italy; the 14.0–km–long Arlberg Tunnel, completed in 1978 in Austria, and the 16.9–km–long St. Gotthard Tunnel, completed in 1980 in Switzerland. In November 27, 2000, the 24.5–km– long Laerdal Tunnel, connecting Laerdal and Aurland in Norway, became the longest land road tunnel (Encyclopedia Americana Online, March 2003), see Table 5.2. Other notable immersed road tunnels constructed in the 20th century include the 3.4–km–long Kanmon Tunnel, completed in 1958, which was driven under the Kanmon Straits and connects Honshu and Kyushu islands in Japan; and the 9.7–km–long Tokyo Aqua Tunnel, constructed under Tokyo Bay and completed in 1997, see Table 5.3.

Tunneling has been very hazardous for maintaining an adequate supply of fresh air for thousands of years. With the mechanization of ventilation equipment, it became possible to eliminate the dangers that accompanied bad ventilation. Therefore, except for the reasons of urbanization, quality aimed environment protection become an important concern for planning a tunnel project (Encyclopedia Americana Online, March 2003). Besides, tunnel projects can probably be built very fast by contemporary technologies; for example, the Laerdal Tunnel took only around five years for construction after it got the permission in 1995 (Marec, 1996), and the

Tokyo Aqua tunnel took about eight and half years (Yamada and Ota, 1999).

From Table 5.1 – 5.3, tunnels could be built longer and longer up to now. However, tunnel disasters have already seriously happened in those above notable tunnels, another point needs be concerned. People may feel tunnels are more dangerous, or have already found out that tunnel accidents are becoming more and more frequent now. For example, in the Alps region, doubling the size of tunnels, building a second tube to separate traffic in the two directions and constructing a third escape tube have been seriously considered as important ideas for improving tunnel safety (Egresi and Lineback, 2001). Hence, in another words, tunnels' system configuration and management for well ventilation, fire protection or disaster response cannot be overlooked, although tunnels can be constructed very fast, long and even under water, the importance of ventilation and related disaster prevention measures cannot be negligible.

Tunnel patterns have close relationship to safety and network configuration, we need briefly discuss different tunnel configuration types, refer to Figure 5.1. For most highways, the tunnel pattern generally is two parallel running tunnels. However, for most railway tunnels, their general pattern is a single running tunnel, because the diameter of a single tunnel can easily accommodate double tracks. But for the railway tunnel with a length greater than 5km, the pattern of two parallel tunnels of single-track is recommended instead of a single running tunnel (Diamantidis et al, 2000, p.139). Sometimes, the service tunnel is required for long tunnels. In addition, in the long railway tunnel, three parallel running tunnels may be considered instead of two parallel running tunnels plus a service tunnel (Diamantidis et al, 2000, p.137).

In order to build up secure network configurations for tunnels, we can summarize three basic tunnel prototypes as the potential targets: a single running tunnel, a pair of running tunnels, and a single service or secondary tunnel. Other tunnel patterns can possibly be composed by these three prototypes. Moreover, ventilation ducts or emergency escape passages connecting individual tunnels may be considered as service tunnels from the shape and the function.

In the next subsection, the surveillance and control issues of tunnels are reviewed.

5.1.2 General supervisory control concerns for tunnels

The material of this subsection is primary referred from: Atkinson, 1997, p.513–516, Bickel et al, 1996, and then substantial data or information including journal contexts will be cited in the brackets for more clearly illustrating the scope of this

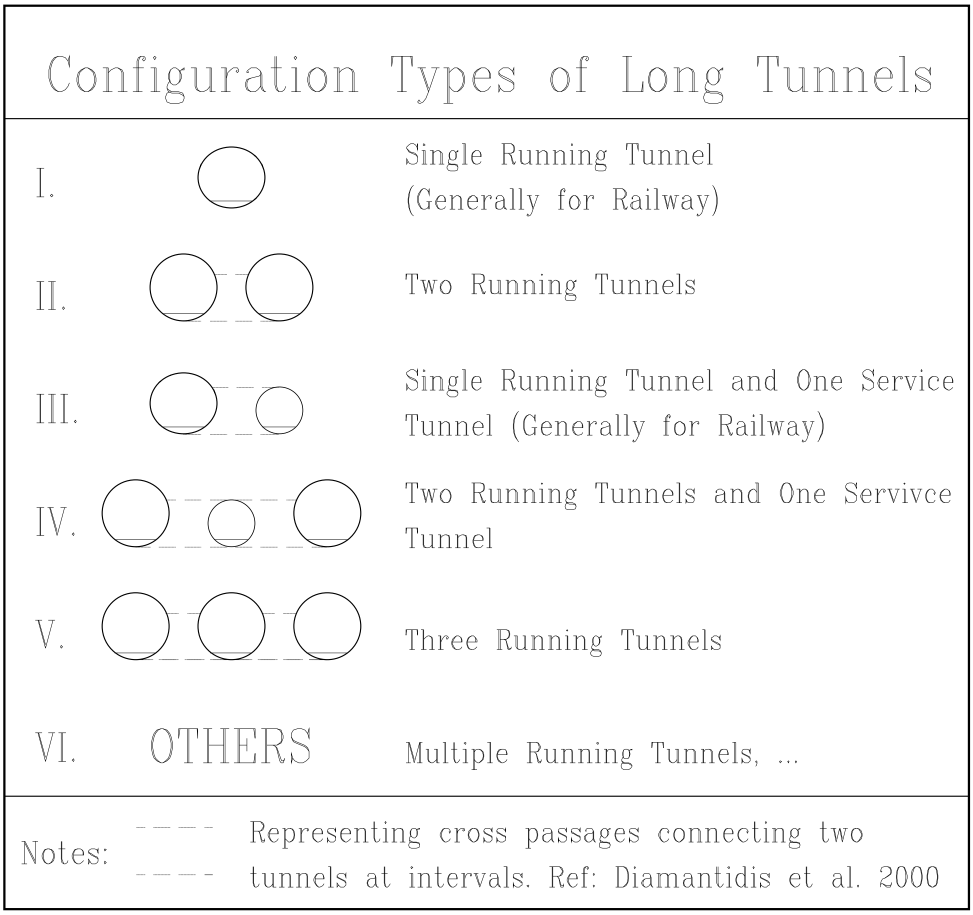


Figure 5.1: Tunnel Configuration Types

subsection.

(1). Communication

The continuous form of radio link has been stressed in long tunnels. This can be provided by the installation of a leaky feeder system throughout.

Emergency telephone points, designed to be vandal resistant by dispensing with handsets, need to be provided at frequent intervals in positions that are accessible but safe for standard drivers. Closed circuit television may also be an advantage, in relaying information on traffic to a central control room with continuous monitoring. Routine maintenance of the above facilities requires regular inspection, testing and the employment of specialist contractors to ensure dependability.

In the renovated Mont-Blanc road tunnel, emergency recesses have been placed alternately at intervals of approximately 100 meters. They are equipped with emergency telephone, fire extinguishers, etc; the sensor can check the existence of fire extinguishers. Fire–fighting facilities, CCTV, telephones and fire trucks are computer-terminal networked (Vuilleumier et al, 2002). In Japan, CCTV is generally required to link with other information equipment such as telephones, push-button type information equipment, and fire detectors in order to turn the camera toward an accident or a fire in a road tunnel (Mashimo, 2002),

(2). Ventilation

Ventilation may rely on the ram effect of traffic, or may also require a controlled fan-assisted system, depending on the length of the tunnel. In addition to periodic maintenance of the machinery, inspection and cleansing of all ducts are necessary. Most systems have automatic smoke and carbon monoxide level monitoring, which needs to be regularly checked. Major tunnels are likely to be provided with computer controlled fans, which, in a fire emergency, can be automatically adjusted for both speed and direction of flow to give maximum control over generated smoke.

High air quality in the tunnel is achieved in two ways, by ventilation and purification. The Laerdal Tunnel is the first in the world to be equipped with an air treatment plant, the air is drawn through a large carbon filter, which removes the nitrogen dioxide. The air quality will be continuously checked and the fans will start automatically when the concentrations of toxic gases exceed specified levels. The fans can also be operated manually from the monitoring center. If any fault should occur in the ventilation system or if any queues should form, creating excessive volumes of exhaust fumes, the tunnel will automatically be closed to traffic.

(www.bergen-guide.com).

(3). Lighting

Lighting produces several maintenance problems as a result of being vulnerable to damage and usually need frequent checking and replacement of outages, especially in areas such as portals where boost lighting ensure a safe transition from daylight conditions. Light conditions should be checked and maintained. Especially in long tunnels, the standby battery lighting leads to the maintenance of necessary air conditioning equipment to prevent deterioration of the batteries. A safe viewing distance of 1000 meters or more is designed in the Laerdahl road tunnel with design speed 80 km per hour (content.engineering.com). In the rail tunnel, the luminance requirement of tunnel environment is generally low and basically for orientation and maintenance, not for passage (Bickel et al, 1996, p.1); however, this concept probably need be adjusted for the sabotage issue, such as 911 terrorism. Lighting for escape is very important; hence the rail tunnel may need similar concern on the lighting for the exit path as the road tunnel. Moreover, providing at least adaptable lighting for capable of detecting abnormal situations and rapidly informing the tunnel work center should also be important for both kinds of tunnels (Diamantidis et al, 2000, Vuilleumier et al, 2002, p.158). Therefore, providing reasonable lighting environment for CCTV cameras is suggested for rail tunnels. CCTV with cameras and infrared image processors is important for ITS as well as for tunnels' intelligence; this will be discussed in the next subsection.

(4). Drainage

Most tunnels rely on pumped systems, and maintenance of the protective features such as grit traps and filters is a critical factor in preserving the equipment. For that electrical equipment, a vital safety aspect is the provision of detailed information and procedures needed to isolate any item or system in the event of accident damage or during maintenance operations.

Poor maintenance results in reduced safety or economy loss for tunnels (Mashimo, 2002); poor drainage may worse lead the whole tunnel filled with water by an unexpected flood (Diamantidis, 2000).

(5). Traffic Control

The control of traffic is vital in the tunnel situation. most tunnels have individual by–laws specifying the nature of controls, which may include: (1). a limit on vehicle dimensions; (2). control of specified goods that are permitted to use the tunnels, e.g. petroleum products, dangerous chemicals and explosives, and limits on vehicle weights. Such by-laws have to be backed up by systematic checking against abuse and commonly there will also be physical control devices, which are subject to regular damage and must be inspected and repaired as part of a program of routine maintenance.

In the renovated Mont-Blanc road tunnel every 600 meters, a lay-by is situated for allowing heavy goods vehicles to stop; every 600 meters a turning bay for allowing maintenance and rescue vehicles to operate in the vehicles (Vuilleumier et al, 2002). In Japan, lay–bys are generally provided at intervals of between 500 and 1500 meters in long road tunnels (Mashimo, 2002). In the Laerdal road tunnel, four sections have been subdivided by means of specially widened areas that are large enough to allow coaches and trains to turn without having to reverse (content.engineering.com).

(6). Fire Risk

Despite the careful regulation of traffic using tunnel, there will remain a risk of fire from fuels normally carried in vehicle, or from faults developed in the necessary service through the tunnel. Attention must be given to the provision and maintenance of well fighting equipment.

Constructing an escape tube is seriously considered as an important idea for improving tunnels' fire safety (Egresi and Lineback, 2001). "Cross-over" passages that allow trains to switch from one track to another are considered in both the Sei-kan tunnel (pref.aomori.jp) and the Channel tunnel; beside the main tunnel (in–between the two train tunnels of the Channel), there is a smaller service tunnel that serves as an emergency escape route, and the safety door for compartment design is considered (Diamantidis, 2000, Eisner, 2000).

Emergency telephones (every 250 meters) and fire extinguishers (every 125 meters) of the Laerdal tunnel have been installed at closer intervals. Computer, monitor or radio link systems for fire service, medical services and other emergency services are designed (content.engineering.com).

(7). Contingency Management

The access difficulties associated tunnels and the sensitivity to stoppage require that emergency procedures are prepared and labor and equipment made available at short notice. Contingencies include the removal of damaged vehicles, demolition and removal of tunnel finishes involved in accidents, clearance of drains and dealing with random breakdown of services and structural elements. To minimize the effects of repairs, a program of regular close inspection is essential, and some work may be done at night.

On May 29, 1999, a construction work affected an accident, and 12 people were killed in the Tauern tunnel, Austria (Leitner, 2001). It is worthwhile to note that an incident of relatively harmless nature may transform to be a disaster (Vuilleumier et al, 2002); a big disaster may be originated from a traffic disturbance or interference which is affected by an ordinary repair work such as the above. Especially in a tunnel's closer, probable darker environment, the driver has rather heavy vision burden, which is an adversary condition for driving (Shaheen and Niemeier, 2000). Therefore, giving fault tolerance for real–time information facilities, or giving spare concern for short–time adjustable facilities such as air handling facilities, to provide more flexible maintenance time and time period for disaster sensitive tunnels should be especially critical.

5.1.3 Distributed intelligence in tunnels

Compared to other information processing networks, a tunnel's SCADA (Bickel, et al, 1996, p.495) network locates in worse environment or has more restricted conditions for repair and maintenance; however, it relates the inescapable responsibility of public safety. Therefore, it is reasonable to take the concept of dual nodes, just as human's two eyes, to take place of the traditional single-node concept for tunnels' SCADA network for assuring node's fault tolerance and for strengthening the capability of data acquisition. Intelligent transportation systems (ITS) are using advanced technologies, especially information technologies in transportation planning and management; a tunnel is a part of a transportation system; hence, some reviews related to the relationship between ITS and the tunnel are discussed in the following.

Advanced technologies of detection and communication systems can make more effective judgment now (Harlow and Peng, 1996). However, the ITS still need better environment of communication media or advanced degree of coordination for assuring information or control can be sent to any place required (Hall, 1995, p.141). In this paper, the desire of Hall is also what this dissertation intends to achieve. It just proposes a distributed and robust network with parallel processing capability to extensively provide transportation information and various mobile communications services, tunnels' environmentally related data or other valuable information for drivers who can prevent from doing something wrong or make correct responses for potential incidents, or even get some personal special behavioral or physiological assistance (Groeger and Rothengatter, 1998 , Shaheen and Niemeier, 2001).

Tunnels can be disaster sensitive places, especially in the earthquake intensive areas such as Taiwan; therefore, related safety and quality factors of tunnels' structure as well as environmental control should be cared for (Wang et al, 2001). Moreover, tunnels are three dimensional objects, even with some rather hidden spaces. Hence, monitoring the movement of the tunnel structure or the distribution of environmental measure–factors with a three–dimensional approach can be an insightful, proactive strategy (La Pointe et al, 1998; Roozenmond, 2001). In this dissertation, the proposed degree–3 network configurations can be more orderly applied to differentiate between front–back information and up–down information, and link them to exclusive terminals. Such an ITS network in the tunnel can have parallel information processing capability to act faster, more comprehensive to correctly discern various abnormal traffic behaviors, structural deterioration, electrical or mechanical disability, poor air quality, water leakage or many other disordered factors.

ITS are oriented for promoting travelers' safety, comfort, convenience and other welfare (Kanninen, 1996), basically, they are quality oriented. However, an unacceptable long loss of telecommunication signals for travelers in especially long tunnels can very easily happen due to some small ordinary faults. Moreover, once an incident happened in a place, some information could not be acquired, travelers might locate in a rather dark space or even in a densely smoky, hot adversary environment that can make both escape and rescue very difficult. Therefore, providing robustness for the telecommunication or SCADA network in the tunnel is just providing travelers well mobile phone services, comfort and life safety in the tunnel. This kind of assurance is just the objective of the ITS. Hence in this dissertation, proposing the SCADA network, which has mathematically proved fault tolerance for the node and the link, as well as a mechanism of working order for checking and maintaining the network system, is considered worthwhile.

CCTV has become a valuable surveillance and control asset for tunnel management (Bickel et al, 1996, p.373, 486, 492). It can be used for incident verification, traffic policy evaluation, and displayed message verification. Lighting environment is related to the installation of CCTV in the tunnel, and this issue has been discussed in the previous subsection. Current CCTV technology allows viewing of 400 to 800 meters in a direction if its visual environment is ideal, and generally is spaced less than 200 meters in the tunnel (Bickel et al, 1996, p.491). One every 150 meters spaced cameras on each wall side are used to ensure surveillance of the renovated

Mont Blanc Tunnel (Vuilleumier et al, 2002). Infrared image processors (cameras) may be needed when light condition is not well (Klein, 2001, p.258–259). CCTV can also apply image–processing techniques to extract traffic movement information for real-time management (Zhang and Forshaw, 1997).

Therefore, CCTV is concerned as an essential element for intelligent transportation systems (McQueen and McQueen, 1999, p.26, 128, 406) as well as for the node element of our proposed SCADA networks in tunnels in this dissertation (Bickel et al, 1996, p.494–495). Since the data process of CCTV may take lots of computing memory; therefore in this dissertation, it is considered that a node represents a terminal which links one CCTV camera as the base together with other detectors or control units to establish up the SCADA network of degree–3 (i.e. honeycomb torus and honeycomb rectangular torus) for the tunnel. However, the proposed network configurations of this dissertation are a kind of systematical architectures, which can also be applied in any terminal as the node, which may or may not link a CCTV camera.

A tunnel is a tube–like space or is a single room; however, it is essentially a large and closed space. The whole space should be surveyed and controlled with a distributed but coordinative real–time processing system. Distributed processing can minimize the severity of a single failure (Bickel et al, 1996, p.495) and also can benefit parallel real-time processing (Zhang and Forshaw, 1997). The distributed intelligence with multiplexing transmission has been considered as the basis of a supervisory control and data acquisition (SCADA) system in the network (Bickel et al, 1996, p.495). However for such large–scale network, a working order for monitoring and checking of the SCADA system is important; this concept for maintaining the ventilation systems, radio connections, lightning systems, traffic lights, emergency equipment, etc., has already been considered in the Laerdal Tunnel, Norway; however, detailed information has not been found yet (content.engineering.coml).

5.1.4 Summary of this section

We can summarize the key concepts reviewed in this section as follows:

(1). Quality or environment protection is becoming important concern for deciding whether a tunnel is built; therefore, especially for lengthy tunneles quality or environment protection should be well designed and continuously controlled.

(2). The lengthy tunnel can probably be constructed very fast by modern technology.

(3). Some people found that tunnel accidents are becoming more and more frequent now, and tunnels' system configuration and management for well ventilation, fire protection or disaster response cannot be overlooked.

(4). An incident of relatively harmless nature can probably transform to be a disaster; fault tolerance and systematical inspection should be concerned especially for important facilities in disaster sensitive tunnels.

(5). CCTV has become a valuable surveillance and control asset for tunnel management or an ITS element.

(6). CCTV can be distibutively planned along the tunnel at intervals of around 150–200 meters, this information can a refeference for estimating the node–scale of a SCADA network in the tunnel.

(7). In the rail tunnel, the lighting requirement of tunnel environment is generally low; however, this concept probably need be adapted for the sabotage issue.

(8). The working order for monitoring and checking of the large–scale SCADA network can be a feature of modern tunnel design.

(9). In a tunnel, providing a SCADA network, which has mathematically proved fault tolerance for the node and the link, as well as a mechanism of working order for

Table 5.4: General Performance of Common Networks

Network	Diameter	Cost	Bisection Width
mesh-connected computer	$2(n)^{0.5}$	$8(n)^{0.5}$	$(n)^{0.5}$
hexagonal mesh	$1.16(n)^{0.5}$	$6.93(n)^{0.5}$	$2.31(n)^{0.5}$
honeycomb mesh	$1.63(n)^{0.5}$	$4.90(n)^{0.5}$	$0.82(n)^{0.5}$
honeycomb rhombic mesh	$2.83(n)^{0.5}$	$8.49(n)^{0.5}$	$0.71(n)^{0.5}$
honeycomb square mesh	$2(n)^{0.5}$	$6(n)^{0.5}$	$0.5(n)^{0.5}$
torus	$(n)^{0.5}$	$4(n)^{0.5}$	$2(n)^{0.5}$
hexagonal torus	$0.58(n)^{0.5}$	$3.46(n)^{0.5}$	$4.61(n)^{0.5}$
honeycomb torus	$0.81(n)^{0.5}$	$2.45(n)^{0.5}$	$2.04(n)^{0.5}$
honeycomb rhombic torus	$1.06(n)^{0.5}$	$3.18(n)^{0.5}$	$1.41(n)^{0.5}$
honeycomb square torus	$(n)^{0.5}$	$3(n)^{0.5}$	$(n)^{0.5}$

checking and maintaining the network system, is considered obeying the objective of developing the ITS.

5.2 Considering Cost and Robustness for Tunnel's SCADA Network

Stojmenovic, 1997 made a comparison for general networks, shown as Table 5.4. We can find the honeycomb tori (including honeycomb rectangular torus and honeycomb rhombic torus) and the hexagonal torus have different merits. The former has rather lower cost; however, the latter looks rather more robust (i.e., the bisection width is larger).

In the previous two chapters, we have proved that the honeycomb tori or generalized honeycomb tori already can have good fault–tolerance capability or robustness. Therefore, we may consider more on the cost factor. Stojmenovic estimated the cost as the product of degree and diameter for a general analysis. Hence, we may need consider a network of less degree–number but with enough fault–tolerance capability. In the next section, we will show that if the network considering both node's and link's fault tolerance, the network's degree should be at least three. In another words, the honeycomb tori or generalized honeycomb tori can be considered for tunnel's SCADA network.

Stojmenovic's comparison considers the length of all links are same from the communication aspect, hence the physical longer wraparound link is essentially deemed with the same length as that of other links. In the real tunnel project, longer link naturally needs higers cost; however, on the comprehensive comparison level, individual detail factor probably can be neglected. Especially, the network well fitted the space is important.

A tunnel is like a tube, and tunnel configuration types have been shown in Figure 5.1. In this research, the HReT for the SCADA network (Bickel et al, 1996, p.495) of a single disaster sensitive tunnel or two parallel disaster sensitive tunnels are proposed as prototypes for adapting (Chown, Kaplan & Kortenkamp, 1995). The master SCADA network of other tunnel configuration may be composed of these above two adaptable proposals. Moreover, instead of the ring, another degree–3 torus network, i.e., GHT(m, 2k, k) and (m-k) even, but with less fault tolerance has also been studied in the previous chapter. It can again possibly be adapted for independent tunnels or tube space with less fault tolerance demand; such as: the service tunnel or the ventilation shaft.

5.3 Dual CCTV Based Nodes for Tunnel's SCADA Network

The CCTV (closed circuit television) is an essential element of the SCADA network of a tunnel (Bickel et al, 1996, p.373, 491) and also an important unit of the intelligent transportation systems (McQueen and McQueen, 1999, p.26, 128, 406). To improve the security of the tunnel systems, experts of the tunnel may suggest the CCTV or other safety related utilities be arranged in a ring network (see Figure

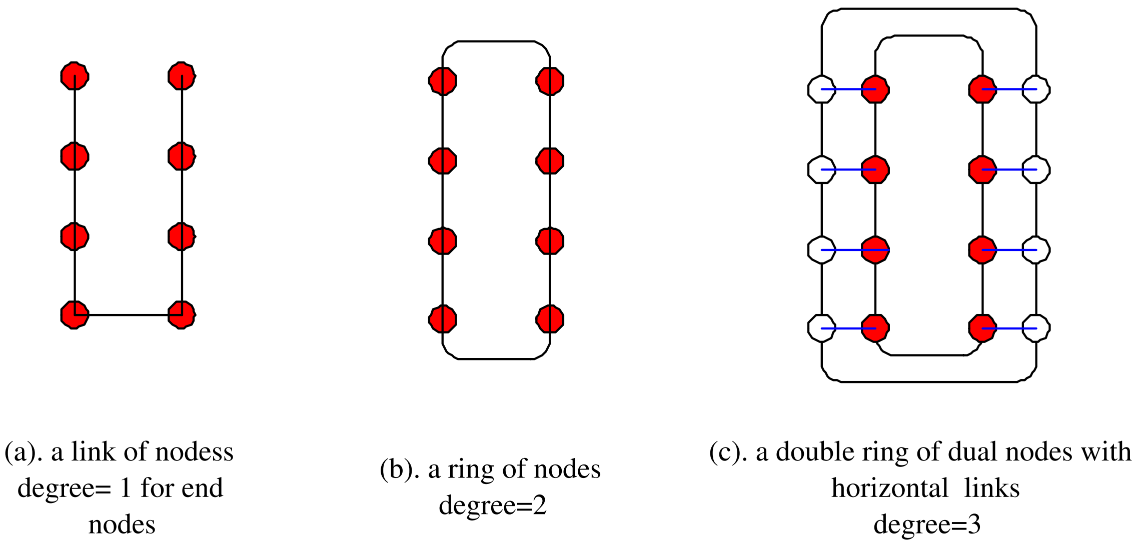


Figure 5.2: The Degree of List, Ring and Double-Ring

5.2), because the ring structure can support operating even if a single link is broken. However, it is still vulnerable, especially when a node is faulty.

Humans' two eyes can give us a solution direction. Just as two eyes can offer more capability of information acquisition and fault tolerance than one eye can, we can apply a set of two CCTV cameras instead of one in tunnel structures or other transportation systems (for example: Chrest et al, 1996, p.127). We can consider that they are two cooperative partners and each is also an independent unit. Then, we can see that the ring network with degree two cannot regularly fit the degree requirement of a network of dual nodes. Each node needs to be connected by its dual

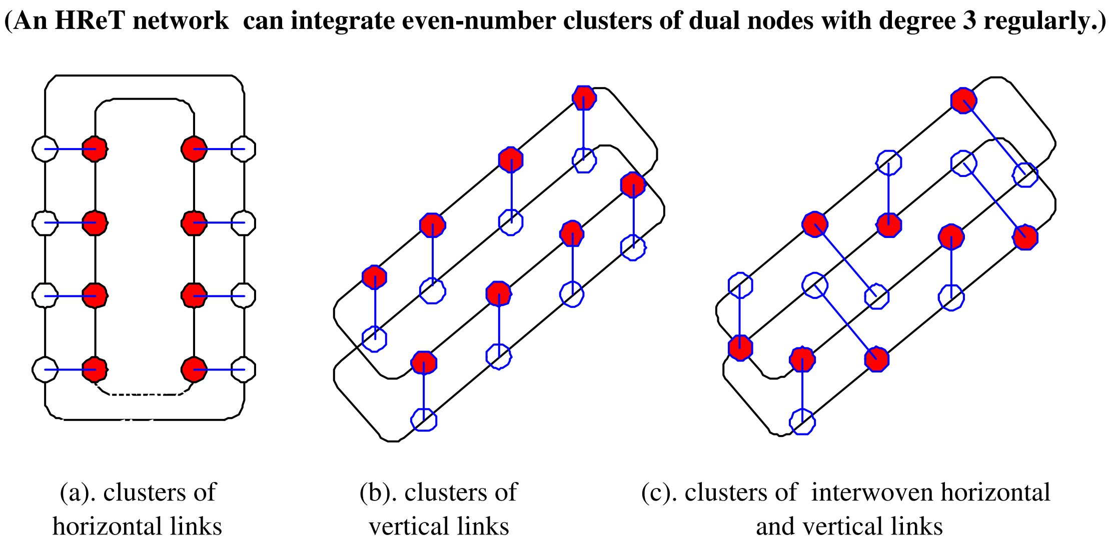


Figure 5.3: A Double-Ring Network Integrates Only Two Rings of Dual Nodes

partner, a forward node and a backward node; therefore, the degree of the network should be at least 3. Hence a double–ring network may be considered; however, it can only integrate two rings of dual nodes (see Figure 5.3 or and Figure 5.5).

In the state of practice, processors can be coordinated as a unit for the best operation, and once a processor of a unit is not good or out of order, the unit can be automatically controlled for the second best operation. HReT or GHT networks with degree–3 can fit the above concept of coordinated unit, and they are naturally more robust than a ring network with degree–2.

Moreover, since the image analysis of CCTV information needs a lot of CPU memory, therefore one terminal is connected with one CCTV camera, and this terminal is arranged as one node for the network of dual–nodes (see Figure 5.4). This network system cannot only have nodes' fault tolerance and provide clearer information, but also may offer a mechanism of parallel processing for real–time management (Zhang and Forshaw, 1997).

We do not mean that each CCTV camera is the only information source for a node in our proposed network prototypes. The CCTV may be replaced by other supervisory sensors in rail tunnels due to light condition. Besides, other safety related sensors and utilities for a zone should be connected and systematically controlled (Bickel et al, 1996, p.453).

However, from item 7 of Section 5.1.4 and the recent sabotage disaster of Taegu subway, South Korea in February 18, 2003, which killed more than 120 people (abcnews.go.com), the installation of an ideal CCTV system may still be needed for correct and real–time incident management in some rail tunnels (Diamantidis et al, 2000, p.139), then the CCTV can be a main information source for a node terminal.

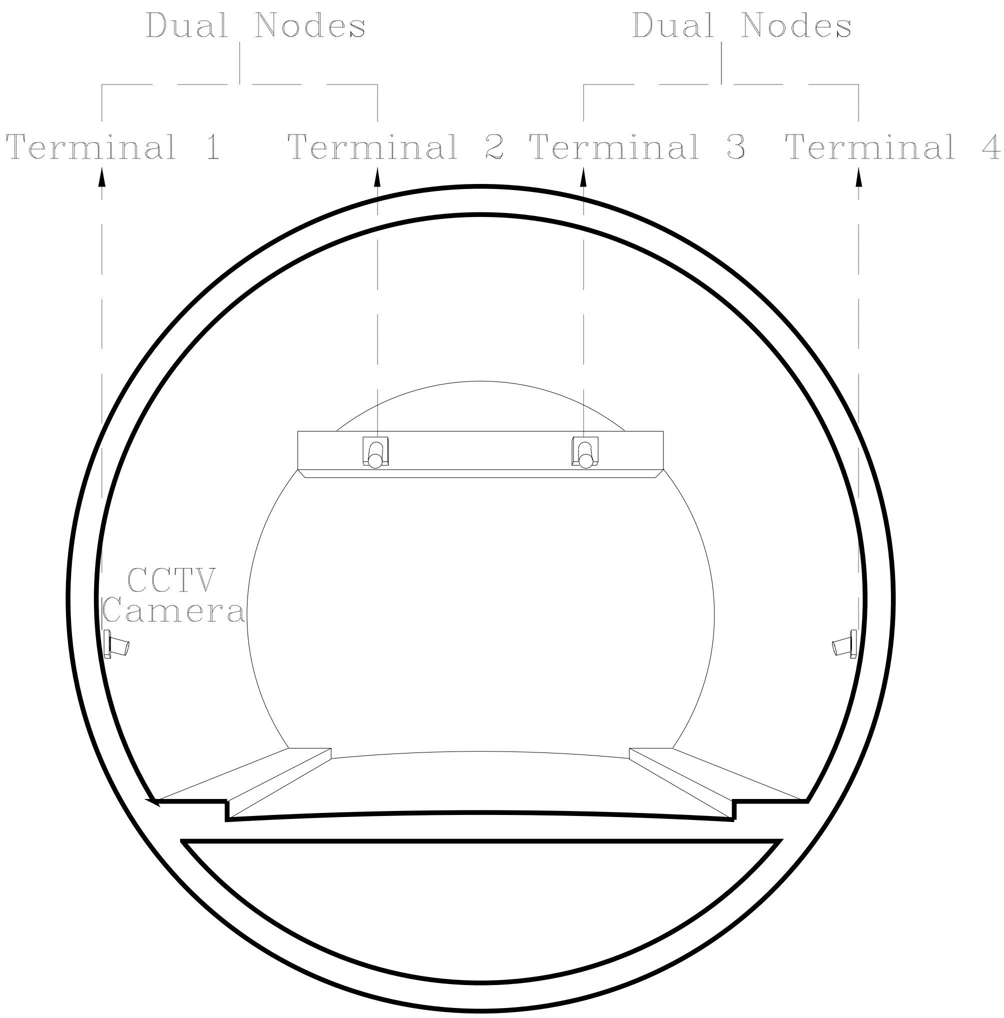


Figure 5.4: Conceptual Tunnel Section

5.4 Hamiltonian Order of the Network as the Base for System Management

Mathematically, a path connects every node once and only once is called a hamiltonian path; and if the first node of the path is linked with the last node, it is called a hamiltonian cycle or simply hamiltonian (Bondy, 1980, p.53). Hamiltonian is in sequential order.

If a network with two adjacent faulty nodes and the network still keeps hamiltonian, then we say this network has "fault tolerance" (Megson, Liu & Yang, 1999). If the network is Hamiltonian and once a link is broken, all nodes can still be connected as a hamiltonian path. The existence of hamiltonian property is a good criterion for evaluating system management for the network of a lot of nodes, because this sequential order is not only good for processing information, but also important for assuring quality of diagnosis, maintenance, and installation of hardware.

In Chapter 3 and 4, we have proved that HReT and GHT networks can have hamiltonian property or more fault tolerance to benefit system management. The proposed networks can be adapted to the rectangular or tunnel space. Besides, they are not expensive, but efficient and robust configurations for diagnosis, maintenance,

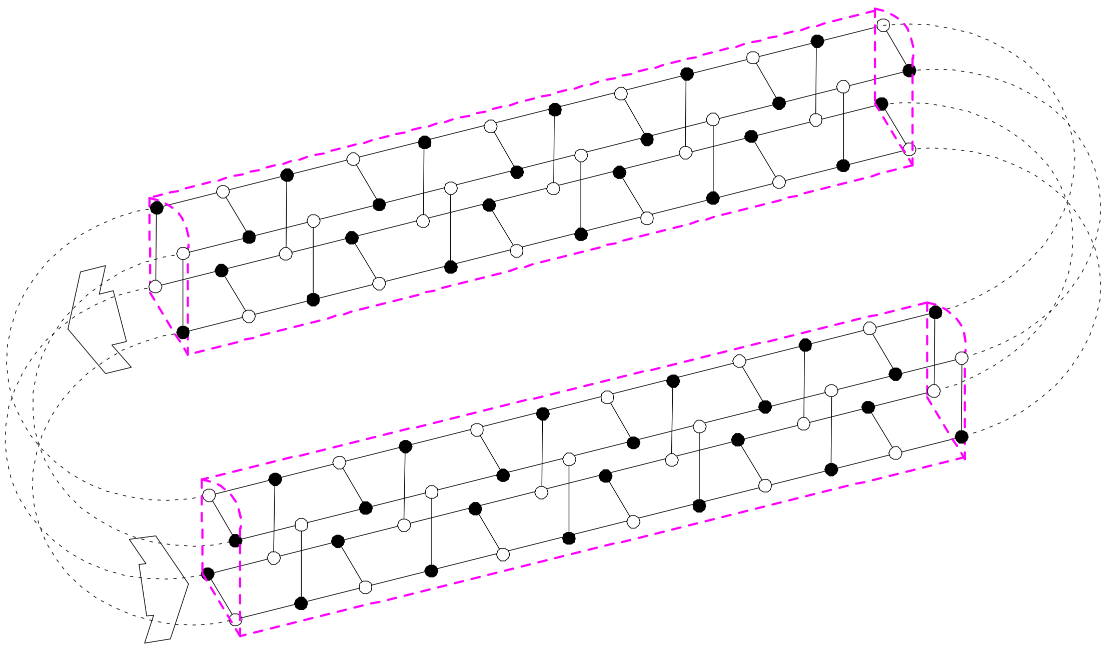


Figure 5.5: HReT for a pair of running tunnels

and renewal without concerning devices at a premium.

5.5 Prototypes with HReT Network for a Single and a Pair of Running Tunnels

The donut–shaped HReT network can be fitted to two parallel tunnels connected together by links as proposed in Figure 5.5. Each tunnel can coordinate with the other.

For long tunnels, separated spaces are generally required, shown as an example in Figure 5.4. For integration concern, these hidden spaces should be monitored and controlled by the network system. The torus network with degree–3 can also fit this requirement.

Tracing along the top and the bottom of a tunnel, we can construct a torus. In Figure 5.6, we propose this network for a high–speed rail (HSR) for its disaster sensitivity. Safety network might be concerned first in the HSR, to detect any small environmental, mechanical or electrical changes and respond correctly and immediately.

This network configuration may need be adapted for specific purposes or specific areas. For example: On link adaptation, the degree of certain nodes can be increased to have more faults tolerance or to form a specific zone such as the portal area or the area near the connecting passages between two tunnels. On axis lines, the number of the axis line can be configured by any positive even number as Theorem 1; but in Figure 5.5, there are $m = 4$ axis lines.

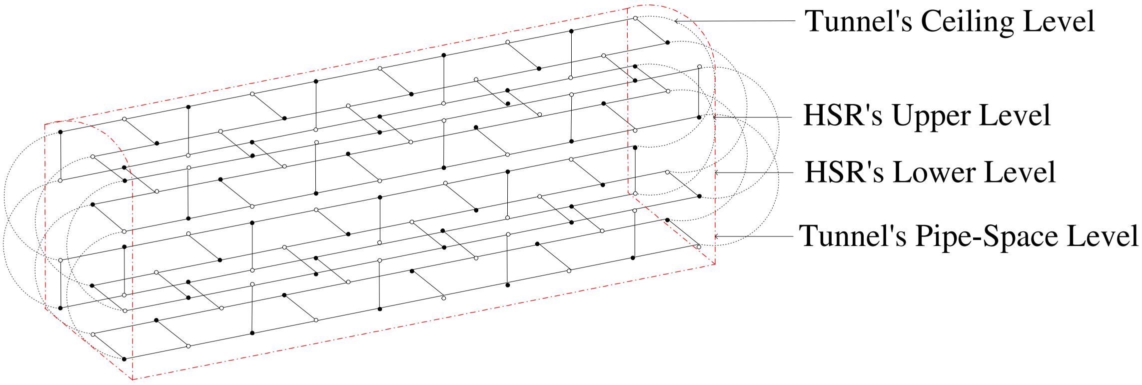


Figure 5.6: HReT for a single running tunnel

5.6 Prototype with GHT network for Service or Secondary tunnels

In Figure 5.6, the HReT network traces along the top and the bottom of a pipe-shaped space. However, even number of axis-lines for both top and bottom is required by HReT configuration. The even number of axis-lines can make sense for the configuration of railway or vehicle roads.

However, the configuration of service lines in tunnels may be different, although the coordination among service lines (or unit of nodes) is still required. In addition, accidents happened in the service tunnel are relatively not so urgent as those happened in the running tunnels. The GHT network follows Theorem 3, which is at least hamiltonian or can have fault tolerance (i.e., at least can keep hamiltonian in the network with a faulty edge), can be applied for such tunnels.

Figure 5.7(b), adapted from Figure 5.7(a), is the 3-dimensional network configuration proposal for service or secondary tunnels. The difference between Figure 5.7(a) and Figure 5.7(b) is that instead of following the sequential sequence of a simple cycle in 5.7(a), in 5.7(b) the second half nodes along the axis-line start from the beginning section of the first half nodes with a pair of wires. The 3–dimensional Figure 5.7(a) looks complicated; however, it is rather simple in the 2–dimensional presentation.

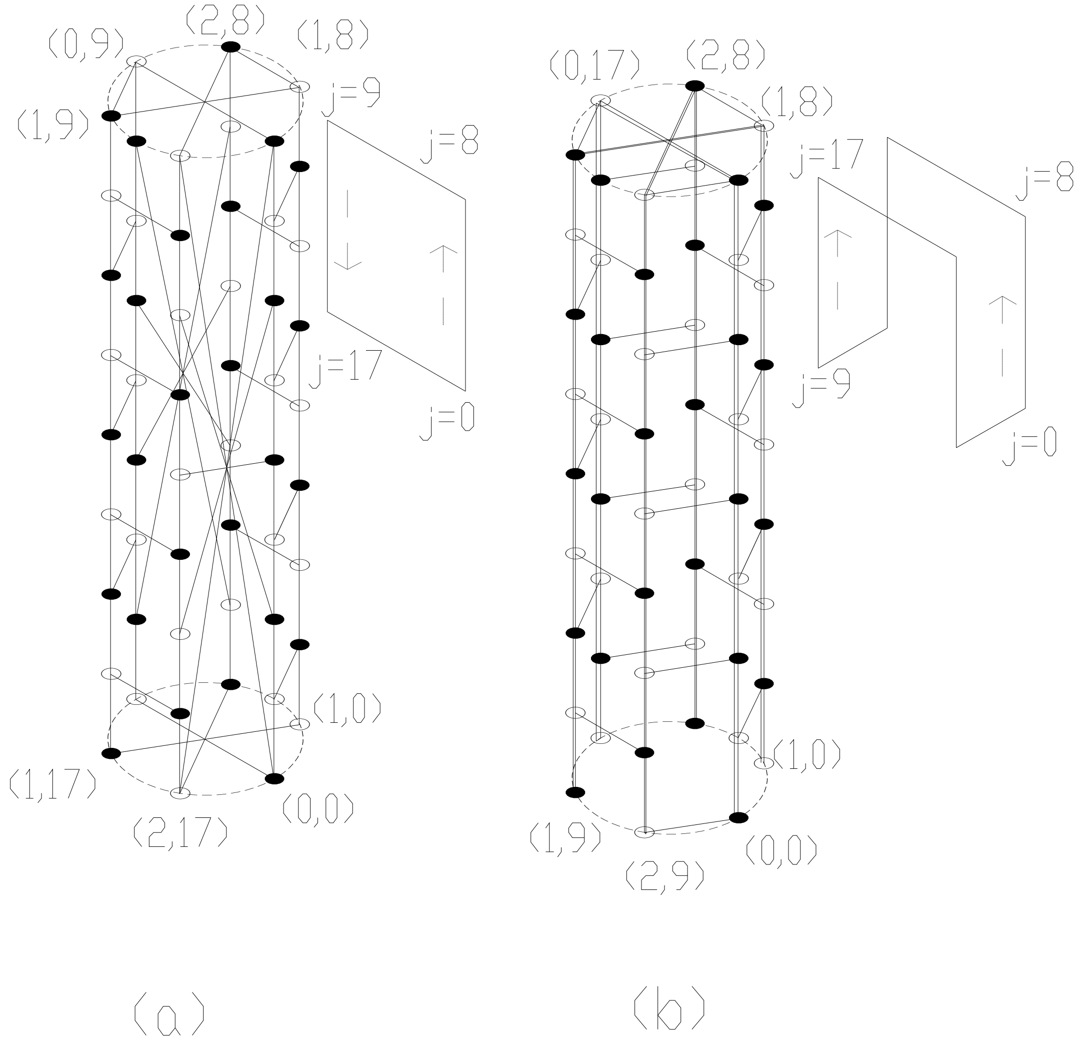


Figure 5.7: (a) 3D of GHT(3,18,9) in Figure 4.1 (d), (b) Adapted of (a) / prototype for service tunnels .

Chapter 6

Conclusions and Suggestions

6.1 Conclusions

In this research, we propose to integrate torus–based networks with the tunnels, such as a single running tunnel, a pair of running tunnels, and a single service tunnel. Dual processors are assumed to be coordinated for the best operation. If one processor of a dual–unit is not good or out of order, this unit needs be automatically controlled for the second best operation. HReT or GHT, as torus–based networks with degree–3 can fit the concept of "coordinated dual–unit", and they are naturally more fault-tolerant than a ring network with degree–2.

For the network of large amounts of nodes and links, giving sequential or hamiltonian order for diagnoses and maintenance can be worthwhile for securing the whole environment. We prove that certain shaped GHT networks, (i.e., GHT(m,2k,k), (m-k) is even), can at least be hamiltonian, and can have fault tolerance (i.e., at least exists a hamiltonian cycle in the network when one link is broken); the HReT network basically can keep hamiltonian "when one link is broken" or "when two nodes of mathematically different corresponding parties are broken".

6.2 Suggestions

Our proposals are prototypes especially proposed for planning disaster sensitive or long tunnels. The HReT network is proposed for critical single or parallel running tunnels. The GHT(m,2k,k) network is proposed for secondary or service tunnels. They are aimed to promote safety, and benefit travelers' welfare in the emerging era of ITS. It is suggested to design a real–time intelligent network with fault tolerance for disaster sensitive tunnels.

In this dissertation, due to: (1) the torus is essentially like a pair of tunnels connected by communication links at both ends, (2) the tunnel disaster is a very critical or typical issue for high–level monitoring and coordinatively controlling; therefore the tunnel is the main target for application.

However, instead of considering a tunnle, we may consider applying similar networks for any important path, which seriously requires coordinatively monitoring and controlling. In most cases paths are double–loaded due to reasonable or economical space–use reason, and they may have critical monitoring or controlling targets at both sides. Depending on our purposes, dual–nodes concept can be applied either along the one–tunnel shaped path or along the two–tunnel shaped path.

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