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Analysis of Modified Fifth Degree Chordal Rings
Bozydar Dubalski, Slawomir Bujnowski, Damian Ledzinski, Antoni Zabludowski and Piotr Kiedrowski
University of Technology and Life Sciences, Bydgoszcz, Poland

1. Introduction

Implementation of new telecommunications services has always been associated with the need to ensure network efficiency required to implement these services. Network efficiency can be described by a number of parameters such as: network bandwidth, propagation time, quality, reliability and fault tolerance. More and better performance, and thus network efficiency is achieved mainly by using more and more advanced technical and technological solutions. There were milestones solutions such as the use of coaxial transmission cables, optical fibers, and various techniques of multiplication like TDM or WDM (Newton, 1996). Significant impact on the way to deliver services had wireless transmission, which has found widespread use in communication networks since the end of last century.

In addition to technical and technological solutions to improve network efficiency by using system solutions such as: protocols or topology (topology control) appropriate for the type of connection or service. Type of system solutions in the network is closely related to the technology involved in the network, so it can be said that technology determines the solutions. Examples may be the different topological approaches as a result or a consequence of the limiters for a specific technology; e.g.:

- Networks based on SONET/SDH have limitations as to the path length (number of nodes in the path) as result of synchronization signals distribution,
- In turn, networks based on WDM technology, where network nodes are OADM (ALU: Alcatel-Lucent, 2011) multiplexers there are restrictions as to the length of the path (in the literal sense) associated with the phenomenon of dispersion,
- Recent example is the WSN networks, which are increasingly common application in various areas of life, such as the implementation of communication solutions for Smart Grid (Al-Karaki, 2004), which dealt with the Authors of this chapter, in the case of WSN network must resolve a number of problems associated with reliable transmission over a large area using short-range devices.

From the above examples it follows that in order to provide high efficiency network technology solutions are not always sufficient and require additional system solutions, which should always go hand in hand with these technological ones. Therefore, proposed in this publication the solutions are always up to date.
2. Background

A critical issue in designing telecommunications systems is choosing the interconnection network topology as it has the biggest impact on efficiency, speed, and reliability of the entire system (Bhuyan, 1987). Nowadays, analysis of regular network structures is one of the most important issues in telecommunications and computer science.

These networks can be modeled by symmetric digraphs, i.e., a directed graph $G$ with vertex set $V(G)$ and edge set $E(G)$, such that, if $[v_i, v_j]$ is in $E(G)$, then $[v_j, v_i]$ is also in $E(G)$. So any edge of digraph connecting vertices $v_i$ and $v_j$ can be replaced by two directed edges $[v_i, v_j]$ and $[v_j, v_i]$ (Narayanan et al., 2001).

It is obvious that the best service and reliability parameters one can obtain by forming complete networks (described by a complete graph), but only small networks can be built in this way. In (Kocis, 1992) a survey of known topologies has been presented. Among the analyzed topologies that would be used in designing the distributed structures, the authors of this publication have chosen rings as they are very simple and extensible. They are characterized by connectivity equal to 2 (damage of one edge or node ensures possibility of transmission), are not expensive (number of edges is equal to the number of nodes), are regular and symmetric, but possess poor transmission parameters.

Halfway between the complete graph and the ring is the chordal ring structure (Arden & Lee, 1981). The chordal ring is a ring with additional chords. It is defined by pair $(p, Q)$, where $p$ is the number of nodes of the ring and $Q$ is the set of chords. Each chord connects every pair of nodes of the ring that are at distance $q_i$ in the ring.

The application of this type of structure is useful due to its simplicity, clear topology, resistance to damages, simplicity of routings, and good extension (Kocis, 1992).

The application of chordal rings in computer systems (Mans, 1999), TDM networks (communication between distributed switching modules) (Bujnowski, 2003), core optical networks (Freire & da Silva, 1999, 2001a, 2001b; Liestman et al., 1998; Narayanan & Opatrny, 1999; Narayanan et al., 2001), and optical access networks (Pedersen, 2005; Pedersen et al., 2004a, 2004b, 2005; Bujnowski et al., 2003) has been analyzed. The authors of this publication, in their earlier works on modeling of telecommunication and computer networks, present an analysis of chordal rings (Bujnowski et al. 2004a, 2004b, 2005).

In the beginning the general definition of chordal ring will be giving.

Definition 1. A chordal ring is a ring with additional edges called chords. A chordal ring is defined by the pair $(p, Q)$, where $p$ denotes the number of nodes of the ring and $Q$ denotes the set of chord lengths $Q \subseteq \{1, 2, ..., \lfloor p/2 \rfloor \}$. Since it is a ring, every node is connected to exactly two other nodes (i.e. assume a numbering of the nodes $1, 2, ..., p$ - then node $i$ is connected to node $i-1$ and $i+1$ (mod $p$). Node 0 is connected to $p$ and 1). Each chord of length $q \in Q$ connects every two nodes of the ring that are at distance $q$. The chordal ring will be further denoted as $G(p; 1, q_i, ..., q_i)$, $q_i < ... < q_i$. In general, the degree of chordal rings is $2i$ unless there is a chord of length $p/2$. In this case $p$ should be even and rings' degree is $2i - 1$ (Gavoille, n.d).

In the papers (Bujnowski et al., 2008a, 2009b, 2010; Dubalski et al., 2007, 2008; Pedersen et al., 2009) the authors have previously analysed the transmission properties of third, fourth
and sixth degree chordal rings and modified graphs of these types. These topologies are the subject of many publications of the researchers from Putra University (Farah et al, 2008, 2010a, 2010b; Azura et al., 2008, 2010; Farah et al. 2010, 2011).

In this publication the survey of the chordal rings consisting of fifth degree nodes (Fig. 1) will be presented. Until now this type of the regular structures is not widely examined, so authors decided to focus on it (Dubalski, 2010).

Fig. 1. An example of chordal ring fifth nodal degree

Average distance and diameter was chosen in order to provide a general and simple indication of transmission properties of the analyzed topologies. These follow standard definitions as summarized below. For more basic definitions of e.g. paths and path lengths, please refer to any basic graph theory book, such as (Distel, 2010).

Definition 2. The diameter $D(G)$ is the largest path length among all of the shortest length of the paths between any pair of nodes. It is defined as follows:

$$D(G) = \max_{v_i, v_j} \{d_{\min}(v_i, v_j)\}$$

where $v_i$ means the number of the node, $d_{\min}$ minimal distance (number of edges) between $i$-th and $j$-th node.

Definition 3. The average path length $d_{av}$ between all pairs of nodes is defined by the formula:

$$d_{av} = \frac{1}{p(p-1)} \sum_{i=0}^{p-1} \sum_{j=0}^{p-1} d_{\min}(v_i, v_j)$$

where $d_{\min}(v_i, v_j)$ is the minimal number of edges between a source node $v_i$ and every other chosen node $v_j$, and $p$ denotes the number of nodes.

A Reference Graph (a virtual example is shown in Fig. 2) can be determined, which presents a reference for all regular graphs of degree 5. It represents lower bounds for average distance and diameter for all these graphs, but since it is a “virtual graph” these bounds may not always be achievable.

The Reference Graph possesses parameters as follows:
1. The number of nodes \( p_{dr} \) in \( d \)-th layer is determined by formula:

\[
p_{1r} = 5
\]

\[
p_{dr} = 20 \cdot 2^{2(d-2)} \text{ when } d > 1
\]

(3)

2. Total number of nodes \( p_{D(G)r} \) versus graph diameter is described by expression:

\[
p_{D(G)r} = \frac{5 \cdot 4^{D(G)r} - 2}{3}
\]

(4)

3. Value of diameter versus total number of nodes can be calculated following formula:

\[
D(G) = \log_4 \left( \frac{3p_r + 2}{5} \right)
\]

(5)

4. Average path length \( d_{av} \) in function of diameter is equal to:

\[
d_{av} = \frac{1 + (3 \cdot D(G)_r - 1) \cdot 4^{D(G)_r}}{3 \cdot (4^{D(G)_r} - 1)}
\]

(6)

5. This graph is symmetrical, its all parameters are equal regardless from which node they are calculated.

![General diagram of virtual infinite Reference Graph](image)

Fig. 2. General diagram of virtual infinite Reference Graph

Only one Reference Graph fifth nodal degree exists in reality, it is the complete graph consisting of 6 nodes.

Two other reference graphs, named as Ideal and Optimal graphs, are also useful for determining average distance and diameter of the chordal rings. They provide theoretical values, which in the following will be compared to values obtained in the real graphs. As for the reference graph mentioned above, the optimal and ideal graphs do not always exist.
In order to determine parameters of the theoretical calculated reference topologies of chordal rings two types of these structures were defined. The first one is called the ideal graph and the second one - optimal graph. In fact these graphs exist only in particular cases, but they are useful as reference models for evaluation expected parameters of tested graphs.

Definition 4. The ideal chordal ring with degree \( D(G) \) is the regular graph with total number of nodes \( p_i \) given by the formula:

\[
p_i = 1 + \sum_{d=1}^{D(G)-1} \lvert p_d \rvert + \lvert p_{D(G)} \rvert
\]

(7)

where \( p_d \) means the number of nodes that belong to the \( d \)-th layer (the layer is the subset of nodes that are at a distance \( d \) from the source node), while \( p_{D(G)} \) denotes the number of the remaining nodes which appear in the last layer. For ideal rings, for every \( n \) and \( m < D(G) \) \( p_n \cap p_m = \emptyset \). If for certain \( D(G) \) the subset \( p_{D(G)} \) of chordal ring reaches the maximal possible value, then such a ring is called the optimal ring (optimal graph).

For ideal chordal ring the average path length \( d_{\text{avi}} \) is expressed as:

\[
d_{\text{avi}} = \frac{\sum_{d=1}^{D(G)-1} d \lvert p_d \rvert + D(G) \lvert p_{D(G)} \rvert}{p_i - 1}
\]

(8)

whereas for the optimal graph the average path length \( d_{\text{avo}} \) is equal to:

\[
d_{\text{avo}} = \frac{\sum_{d=1}^{D(G)} d \ lvert p_d \rvert}{p_o - 1}
\]

(9)

where \( d \) – layer number, \( p_d \) – number of nodes in \( d \)-th layer, \( p_o \) – number of nodes in optimal graph.

Optimal graphs were used to calculate the formulas describing parameters of each type of analyzed chordal ring, whereas ideal rings were served to compare calculated theoretically and obtained in reality parameters of analyzed structures.

The basic topology of fifth degree chordal rings in Fig. 3 is shown. The definition, short presentation and author’s consideration concerned of this structure are given below.

Fig. 3. Basic chordal ring fifth nodal degree CHR5(20; 3,10)
Definition 5. The basic chordal ring fifth nodal degree called CHR5 is an undirected graph, based on a cycle with additional connections (chords). It is denoted by CHR5(p; q1,q2) where p must be even and means number of nodes creating the ring, chord length q1 > p/2 is odd, even too, chord length q2 is equal to p/2. The values of p and q1 must be prime each other (Bujnowski, 2011).

In order to calculate the diameters and average path lengths appearing in optimal graphs it is necessary to evaluate the maximal number of nodes appearing in each layer. In the table 1 the numbers of nodes in the first successive layers of virtual optimal ring are shown (d denotes the layer number, pd - the number of nodes appearing in d-th layer).

| d  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|----|----|----|----|----|----|----|----|----|
| pd | 5  | 12 | 20 | 28 | 36 | 44 | 52 | 60 |

Table 1. Maximal number of nodes in the layers

If d > 1 the power of these sets is described by formula:

\[ p_{do} = 4(2d - 1) \]  

(10)

Using the formula given above, the total number of nodes po in the optimal graph with diameter D(G) can be calculated (D(G) > 1):

\[ p_o = 4D(G)^2 + 2 \]  

(11)

The total number of nodes in optimal graphs versus its diameter is shown in table 2.

| d(G) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|------|----|----|----|----|----|----|----|----|
| pd  | 6  | 18 | 38 | 66 | 102| 146| 198| 258|

Table 2. Total numbers of nodes forming optimal graphs versus diameter

The average path length in optimal graphs is given by formula:

\[ d_{ave} = \frac{8D(G)^3 + 6D(G)^2 - 2D(G) + 3}{3(4D(G)^2 + 1)} \]  

(12)

Only one optimal graph exists in reality. It is the complete graph which possesses 6 nodes, but the ideal chordal rings can be found. Whereas it founded two groups of ideal graphs consisting of p nodes, which can be described by formulas given below.

The graphs belonging to the first group are defined as follows:

\[ p_i = 4D(G)^2 \quad (D(G) > 1) \]  

(13)

so

\[ D(G) = \sqrt[2]{\frac{p_i}{2}} \]  

(14)
In this case a chord length $q_1$ of ideal graphs is equal to:

$$q_1 = 2D(G) - 1 \quad \text{or} \quad q_1 = 2D(G) + 1$$

$$q_1 = \sqrt{p_i} - 1 \quad \text{or} \quad q_1 = \sqrt{p_i} + 1$$

(15)

these both graphs are isomorphic each other.

The average path length can be express by formula:

$$d_{avr} = \frac{8D(G)^3 + 3D(G)^2 - 8D(G) + 3}{3(4D(G)^2 - 1)}$$

(16)

The graphs belonging to the second group are described as follows:

If $D(G) > 2$ then:

$$p_i = 4D(G)^2 - 4D(G) = 4D(G) [D(G) - 1]$$

(17)

So when the number of nodes is equal to $p_i$ then

$$D(G) = \frac{1 + \sqrt{1 + p_i}}{2}$$

(18)

The lengths of chords used to construct ideal graphs can be calculated using formulas:

$$q_1 = 2D(G) - 1 \quad \text{or} \quad q_1 = \sqrt{1 + p_i}$$

(19)

When the number of nodes creating chordal ring is given by equation:

$$p_i = 4(9i^2 + 9i + 2) \quad \text{or} \quad p_i = 6(6i^2 + 10i + 4) \quad \text{where} \quad i \in \{1, 2, \cdots, n\}$$

then

$$q_1 = 2D(G) + 1 \quad \text{or} \quad q_1 = \sqrt{p_i + 1} + 2$$

if $p_i = 4(9i^2 + 9i + 2)$ then

$$q_1 = \frac{4D(G)^2 - 2D(G) - 3}{3}$$

(20)

if $p_i = 6(6i^2 + 10i + 4)$ then

$$q_1 = \frac{4D(G)^2 - 6D(G) + 3}{3}$$

The average path length of all these graphs is described by formula:

$$d_{avr} = \frac{8D(G)^3 - 6D(G)^2 - 8D(G) + 3}{3(4D(G)^2 + 4D(G) - 1)}$$

(21)

Unfortunately the parameters of CHR5 graphs are considerably different of Reference Graph parameters, what is shown in fig. 4 and 5 given above.

It follows from the difference of number of nodes appearing in successive layers and thus the difference of total number of nodes appearing in dependence of its diameter as well.

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The aim of authors of this publication was to find structures possessing basic parameters which values would be closer to reference graph parameters.

3. Analysis of modified graphs fifth degree

The authors prepared two programs which were used to make it possible to examine the analysed graphs - “Program Graph Finder” and “Find the best distribution of nodes in the layers”. The first one - “Program Graph Finder” was used in the first stage of analysis for quite simple topologies, the second one “Find the best distribution of nodes in the layers” – for more complicated structures, when the number of variables describing the way of connections is greater than 4.

The real values of parameters of modified chordal rings were calculated using these programs and compared to those obtained in a theoretical way.

In the following sections, an analysis of 15 different regular structures based on chordal rings is presented. Each of the type of graphs is defined, examples are given, the distribution of nodes in different layers is analyzed, and the ideal and optimal graphs are compared to real graphs. Also, basing on the analysis of nodes in different layers, the average distance and diameter can be calculated as a function of the number of nodes.

The graphs are divided into 3 groups, each consisting of 5 types of graphs. The first group of graphs needs to have a number of nodes divisible by two, and the second group of graphs a
number of nodes divisible by 4. The third group of graphs also has a number of nodes divisible by 4, but for these no mathematical expressions of node distribution (and thus the average distance and diameter) were found.

3.1 First group of chordal rings

As previously mentioned, for each type of graph we present:

- Definitions
- Descriptions
- Distribution of nodes
- Expressions for key parameters
- Comparisons of parameters for real and theoretical graphs.

Graph CHR5_a.

Definition 6. The modified fifth degree chordal rings called CHR5_a (Fig. 6) is denoted by CH\textsubscript{R}5\_a(\textit{p}; \textit{q}_1, \textit{q}_2), where \textit{p} is even and means number of nodes; \textit{q}_1, \textit{q}_2 are chords. Chords \textit{q}_1 and \textit{q}_2 are odd and < p/2. Chord \textit{q}_1 generates a Hamiltonian cycle, whereas \textit{q}_2 is odd too and < p/2. Each even node \textit{i}_{2k} is connected to five other nodes: \textit{i}_{2k+1}, \textit{i}_{2k+1}, \textit{i}_{2k+q_1(\text{mod } p)}, \textit{i}_{2k+q_1(\text{mod } p)}, \textit{i}_{2k+q_2(\text{mod } p)}(0 \leq k < p/2). The values of \textit{p} and \textit{q}_1 must be prime each other (this ensures that the Hamiltonian cycle is created).

In table 3 the numbers of nodes in the layers of optimal rings as the function of node degree are shown.

| \textit{d} | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|
| \textit{p}_{do} | 5   | 16  | 33  | 58  | 89  | 128 | 173 | 226 |

Table 3. Maximal number of nodes in the successive layers

When \textit{d} (layer number) is odd, then the power of these sets is described by the expression:

\[
\textit{p}_{do\_odd} = \frac{1}{2}(7\textit{d}^2 + 3)
\]

and when \textit{d} is even:

\[
\textit{p}_{do\_even} = \frac{1}{2}(7\textit{d}^2 + 3)
\]
The general expression has the following form:

\[ p_{do} = \frac{1}{2} (7d^2 + 4 - d \mod 2) \]  

(24)

The total number of nodes \( p_o \) forming an optimal graph which possesses diameter \( D(G) \) is expressed as:

\[ p_o \text{ odd} = \frac{7}{12} (2D(G)^3 + 3D(G)^2 + 4D(G)) + \frac{3}{4} \]

\[ p_o \text{ even} = \frac{7}{12} (2D(G)^3 + 3D(G)^2 + 4D(G)) + 1 \]

\[ p_o = \frac{7}{12} (2D(G)^3 + 3D(G)^2 + 4D(G)) + 1 - \frac{D(G) \mod 2}{4} \]  

(25)

which confirms the results obtained by constructing the possible graphs, as shown in Table 4.

| \( D(G) \) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| \( p_o \) | 6 | 22 | 55 | 113 | 202 | 330 | 503 | 729 |

Table 4. Diameters and total numbers of nodes in virtual, optimal graphs

The average path length in optimal graphs can be calculated as:

\[ d_{avo} = \frac{3}{2} \frac{7D(G)^4 + 14d(G)^3 + 14d(G)^2 + 8d(G) - 2d(G)d(G) \mod 2 - d(G) \mod 2}{14d(G)^3 + 21d(G)^2 + 28d(G) - 3d(G) \mod 2} \]  

(26)

Fig. 7 shows a comparison of diameters and average path lengths between theoretical and real graphs.

Fig. 7. Comparison of diameter and average path length of theoretical and real graphs CHR5_a
All graphs of this type are symmetrical, the values of their basic parameters do not depend on the number of source node.

**Graph CHR5_b.**

Definition 6. The modified fifth degree chordal ring called CHR5_b is denoted by CHR5_b(p; q_1, q_2, q_3) where p is even and means number of nodes; q_1, q_2, q_3 are chords, where chord q_1 and q_2 possess even lengths, whereas the length of q_3 is odd. The values of p and q_1, q_2, q_3 must be lower than p/2. Each even node i_2k is connected to five other nodes: i_2k-1, i_2k+1, i_2k-1+q_1(mod p), i_2k+1+q_1(mod p), i_2k+1+q_3(mod p), while odd node i_2k+1 is connected to i_2k, i_2k+2, i_2k+1-2q_1(mod p), i_2k+1+q_2(mod p) and i_2k+2-q_1(mod p) (0 ≤ k < p/2).

![Fig. 8. Modified chordal ring CHR5_b(20; 2,6)](image)

Fig. 8 shows an example of CHR5_b. In table 5, the numbers of nodes in the layers of an optimal graph is shown.

| d  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|----|----|----|----|----|----|----|----|----|
| p_o | 5  | 20 | 61 | 140| 267| 454| 713| 1056|

Table 5. Maximal number of nodes in the layers

When d is bigger than 2, the maximal number of nodes which can appear in the successive layers is described by:

\[ p_o = 2d^3 + 5d - 8 \]  

(27)

The total number of nodes p_o in the optimal graph with diameter D(G) > 1 is given by:

\[ p_o = \frac{1}{2} \left( D(G)^4 + 2D(G)^3 + 6D(G)^2 - 11D(G) + 18 \right) \]  

(28)

This was also confirmed by constructing the possible graphs. These results can be seen in Table 6.

| d(G) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|------|----|----|----|----|----|----|----|----|
| p_o  | 6  | 26 | 87 | 227| 494| 948| 1661| 2717|

Table 6. Total numbers of nodes in optimal graphs versus diameter

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The average path length in optimal graphs can be expressed as:

\[
d_{\text{ave}} = \frac{12D(G)^5 + 30D(G)^4 + 70D(G)^3 - 45D(G)^2 - 97D(G) + 300}{15(D(G)^4 + 2D(G)^3 + 6D(G)^2 - 11D(G) + 16)}
\]  

(29)

Fig. 9. Comparison of diameter and average path length of theoretical and real graphs CHR5_b

Fig. 9 shows a comparison of the diameter and average path length between theoretical and real graphs.

Not all these graphs are symmetric, but most of the graphs possessing parameters equal or close to ideal graphs are symmetric. In table 7 examples of the real and ideal chordal rings are presented.

| Number of nodes | \( q_1 \) | \( q_2 \) | \( q_3 \) | \( d_{\text{ave}} \) |
|-----------------|------|------|------|----------------|
| 8               | 2    | 2    | 3    | 1.2857143     |
| 10              | 2    | 4    | 3    | 1.4444444     |
| 12              | 2    | 2    | 5    | 1.5454545     |
| 14              | 2    | 2    | 7    | 1.6153846     |
| 16              | 2    | 6    | 7    | 1.6666666     |
| 18              | 2    | 4    | 7    | 1.7058823     |
| 38              | 6    | 12   | 9    | 2.1891892     |
| 40              | 6    | 18   | 9    | 2.2307692     |
| 42              | 4    | 8    | 19   | 2.2682927     |
| 44              | 6    | 18   | 15   | 2.3023255     |
| 46              | 4    | 8    | 19   | 2.3333333     |
| 48              | 10   | 22   | 7    | 2.3617022     |
| 48              | 14   | 22   | 17   | 2.3617022     |
| 50              | 4    | 8    | 21   | 2.3877552     |
| 52              | 10   | 14   | 17   | 2.4117646     |
| 54              | 4    | 14   | 23   | 2.4339623     |
| 56              | 10   | 22   | 5    | 2.4545455     |
| 58              | 4    | 14   | 23   | 2.4736843     |

Table 7. Examples of ideal graphs CHR5_b
Graph CHR5_c

Definition 7. The modified fifth degree chordal ring called CHR5_c is denoted by CHR5_c(p; q₁, q₂, q₃), where p is even and means number of nodes; q₁, q₂, q₃ are chords, all chords possess odd lengths less than p/2. The values of p and q₁, q₂, q₃ must be prime each other. Each even node \(i_{2k}\) is connected to five other nodes: \(i_{2k-1}\), \(i_{2k+1}\), \(i_{2k+q₁(mod\ p)}\), \(i_{2k+q₂(mod\ p)}\), \(i_{2k+q₃(mod\ p)}\). While odd node \(i_{2k+1}\) is connected to \(i_{2k}\), \(i_{2k+2}\), \(i_{2k+1-q₁(mod\ p)}\), \(i_{2k+1-q₂(mod\ p)}\) and \(i_{2k+1-q₃(mod\ p)}\) where \(0 \leq k < p/2\).

Fig. 10 shows an example of CHR5_c. In Table 8 the numbers of nodes in the layers of an optimal graph is shown.

| \(d\)  | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| \(p_{do}\) | 5   | 20  | 50  | 110 | 200 | 340 | 550 | 850 |

Table 8. Number of nodes appearing in successive layers

In the case when \(d\) – number of layer is bigger than 2 the number of nodes in the layers can be described by the following expression:

\[
p_{do} = 5 \left( \frac{2}{3}d^3 - 5d^2 + \frac{67}{3}d - 30 \right)
\] (30)

The total number of nodes \(p_o\) in the optimal graph with diameter \(D(G) > 1\) is given by:

\[
p_o = \frac{1}{6}(5D(G)^4 - 40D(G)^3 + 265D(G)^2 - 590D(G) + 516)
\] (31)

In table 9 the total number of nodes in virtual, optimal graphs, as described by the above expression, is shown.

| \(D(G)\) | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|
| \(p_o\)  | 6   | 26  | 76  | 186 | 386 | 726 | 1276| 2126|

Table 9. Total numbers of nodes in optimal graphs

The average path length in optimal graphs can be calculated using the expression:
Fig. 11. Comparison of diameter and the average path length between theoretical and real CHR5_c graphs.

Fig. 11 shows a comparison of diameter and the average path length between theoretical and real graphs. All graphs of this type are symmetrical, but they couldn’t find any ideal graph.

**Graph CHR5_d.**

Definition 8. The modified fifth degree chordal ring called CHR5_d is denoted by CHR5_d(p; q_1,q_2,p/2), where p means the number of nodes and is positive and even; q_1, q_2 are chords which possess odd lengths less than p/2. The values of p and q_1, q_2 must be prime each other. Each even node i_2k is connected to five other nodes: i_2k-1, i_2k+1, i_2k+q_1(mod p), i_2k+q_2(mod p) while odd node i_2k+1 is connected to i_2k, i_2k+2, i_2k+1-q_1(mod p), i_2k+1-q_2(mod p) and i_2k+1+p/2(mod p) where (0 ≤ k < p/2).

Fig. 12. Example of modified chordal ring CHR5_d(16; 3,5,8)

Fig. 12 shows an example of CHR5_d. In table 10, the numbers of nodes in the layers of an optimal graph are shown. It should be noted that there are two different number of nodes in layers, depending on whether the total number of nodes is divisible by 4 or not.

| d    | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|------|----|----|----|----|----|----|----|----|
| p_0=0 (mod 4) | 5  | 16 | 36 | 66 | 106| 156| 216| 286|
| p_0≠0 (mod 4) | 5  | 18 | 39 | 72 | 113| 166| 227| 300|

Table 10. Maximal number of nodes in the successive layers.
When the number of layer \(d\) is bigger than 1, the number of nodes in the layers can be described by the following expression:

\[
\begin{align*}
\text{If } p = 0 \pmod{4} & \text{ then } p_{d0} = 5d^2 - 5d + 6 \\
\text{if } p \neq 0 \pmod{4} \text{ and layer number is even} & \text{ then } p_{d0} = 5d^2 - 3d + 4 \\
\text{if } p \neq 0 \pmod{4} \text{ and layer number is odd} & \text{ then } p_{d0} = 5d^2 - 3d + 3 \\
\end{align*}
\]

(33)

The total number of nodes \(p_o\) in the optimal graph depending on the diameter is given by:

\[
\begin{align*}
p_o = \frac{D(G)(4D(G)^2 + 13)}{3} & \text{ if } p_o = 0 \pmod{4} \\
p_o = \frac{D(G)(10D(G)^2 + 6D(G) + 17)}{6} + 1 & \text{ if } p \neq 0 \pmod{4} \text{ and } D(G) \text{ is even} \\
p_o = \frac{D(G)(10D(G)^2 + 6D(G) + 17)}{6} + \frac{1}{2} & \text{ if } p \neq 0 \pmod{4} \text{ and } D(G) \text{ is odd} \\
\end{align*}
\]

(34)

In Table 11 the total number of nodes in virtual optimal graphs described by formula given above is shown.

| \(D(G)\) | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|
| \(p_o = 0 \pmod{4}\) | 6   | 22  | 58  | 124 | 230 | 386 | 602 | 888 |
| \(p_o \neq 0 \pmod{4}\) | 6   | 24  | 63  | 135 | 248 | 414 | 641 | 941 |

Table 11. Total numbers of nodes forming optimal graphs versus diameter

The average path length in optimal graphs can be calculated using the expressions:

\[
\begin{align*}
\text{If } p_o = 0 \pmod{4} & \text{ then } d_{av} = \frac{D(G)(2D(G)^4 + 5D(G)^3 + 12D(G)^2 + 10D(G) + 1)}{2(5D(G)^3 + 13D(G) - 3)} \\
\text{if } p_o \neq 0 \pmod{4} & \text{ then } d_{av} = \frac{6D(G)(5D(G)^2 - 3D(G) + 3 + (D(G) + 1) \pmod{2})}{D(G)(10D(G)^2 + 6D(G) + 17) + 3 + 3(D(G) + 1) \pmod{2}} \\
\end{align*}
\]

(35)

Fig. 13. Comparison of diameter and average path length of theoretical and real graphs CHR5_d

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Fig. 13 shows a comparison of diameter and average path length between theoretical and real graphs.

All this type of chordal rings are symmetrical. Ideal graphs are only for the cases where the number of nodes is divisible by 4. Examples are given in Table 12.

| Number of nodes | q₁ | q₂ | p/2 | d̅av |
|-----------------|----|----|-----|------|
| 12              | 3  | 5  | 6   | 1.545455 |
| 16              | 3  | 5  | 8   | 1.666667 |
| 28              | 7  | 11 | 14  | 2.037037 |
| 32              | 5  | 13 | 16  | 2.16129 |
| 36              | 5  | 13 | 18  | 2.257143 |
| 40              | 7  | 17 | 20  | 2.333333 |
| 44              | 5  | 13 | 22  | 2.395349 |
| 52              | 5  | 17 | 26  | 2.490196 |
| 76              | 13 | 21 | 38  | 2.893333 |
| 80              | 7  | 25 | 40  | 2.949367 |
| 84              | 9  | 23 | 42  | 3.00000 |
| 88              | 7  | 27 | 44  | 3.045977 |
| 96              | 7  | 29 | 48  | 3.126316 |

Table 12. Examples of ideal graphs CHR₅_d

Graph CHR₅_e.

Definition 9. The modified fifth degree chordal ring called CHR₅_e(p; q₁,q₂,p/2), where p means the number of nodes and is positive and even; q₁, q₂ are chords which possess even lengths less then p/2. The values of p/2 and q₁, q₂ must be prime each other. Each even node i₂k is connected to five other nodes: i₂k-1, i₂k+1, i₂k+q₁(mod p), i₂k-q₁(mod p) and i₂k+p/2(mod p) where (0 ≤ k < p/2).

Fig. 14. Example modified chordal ring CHR₅_e(18; 4,8,9)

Fig. 14 shows an example of CHR₅_e. In Table 13 the number of nodes appearing in the successive layers of optimal graphs is shown. It should be observed that there are two different number of nodes in layers, depending on the total number of nodes are they divisible by 4 or not.
Analysis of Modified Fifth Degree Chordal Rings

Table 13. Maximal number of nodes in the successive layers

| \( d \) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|-------|----|----|----|----|----|----|----|----|
| \( p_o \equiv 0 \pmod{4} \) | 5  | 16 | 42 | 88 | 152| 232| 328| 440|
| \( p_o \not\equiv 0 \pmod{4} \) | 5  | 18 | 48 | 96 | 160| 240| 336| 448|

When the number of layers \( d \) is bigger than 1 the number of nodes in the layers can be described by the following expressions:

\[
\begin{align*}
\text{if } p \equiv 0 \pmod{4} \text{ and } d \geq 2 \text{ then } & \quad p_{o_d} = 8d(d - 1) \\
\text{if } p \not\equiv 0 \pmod{4} \text{ and } d \geq 3 \text{ then } & \quad p_{o_d} = 8d(d - 1) - 8
\end{align*}
\]  

(36)

The total number of nodes \( p_o \) in the optimal graph depending on the diameter is given by:

\[
\begin{align*}
\text{if } p \equiv 0 \pmod{4} \text{ and } D(G) \geq 2 \text{ then } & \quad p_o = \frac{8D(G)^3 - 32d(G) + 72}{3} + \frac{8D(G)(D(G)^2 - 4)}{3} + 24 \\
\text{if } p \not\equiv 0 \pmod{4} \text{ and } D(G) \geq 1 \text{ then } & \quad p_o = \frac{8D(G)^3 - 8d(G) + 24}{3} + \frac{8D(G)(D(G)^2 - 1)}{3} + 8
\end{align*}
\]  

(37)

In Table 14 the total number of nodes in virtual optimal graphs described by the above expressions is shown.

Table 14. Total numbers of nodes forming optimal graphs versus diameter

| \( D(G) \) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|-------|----|----|----|----|----|----|----|----|
| \( p_o \equiv 0 \pmod{4} \) | 6  | 22 | 64 | 152| 304| 536| 864| 1304|
| \( p_o \not\equiv 0 \pmod{4} \) | 6  | 24 | 72 | 168| 328| 568| 904| 1352|

The average path length in optimal graphs can be calculated using this expression:

\[
\begin{align*}
\text{When } p_o & \equiv 0 \pmod{4} \text{ and } D(G) \geq 2 \text{ then } \\
\text{when } p_o & \not\equiv 0 \pmod{4} \text{ and } D(G) \geq 1 \\
\end{align*}
\]

\[
d_{av} = \frac{6D(G)^4 + 4D(G)^3 - 18D(G)^2 - 16D(G) + 105}{8D(G)^3 - 32D(G) + 69} \\
\]

(38)

Fig. 15. Comparison of diameter and average path length of theoretical and real graphs CHRS_e
Fig. 15 shows diameter and average path lengths in theoretical and real graphs with up to 100 nodes.

Some but not all of these graphs are symmetric, and as illustrated in Fig. 15 the non-symmetric graphs generally have parameters closer to those of ideal graphs. Only a few ideal graphs are found, of which some examples are shown in Table 15.

| Number of nodes | $q_1$ | $q_2$ | $p/2$ | $d_{av}$  |
|-----------------|-------|-------|-------|-----------|
| 10              | 2     | 4     | 5     | 1,444444  |
| 12              | 2     | 2     | 6     | 1,545455  |
| 14              | 2     | 4     | 7     | 1,615385  |
| 16              | 2     | 6     | 8     | 1,666667  |
| 28              | 6     | 10    | 14    | 2,037037  |
| 32              | 6     | 10    | 16    | 2,161290  |
| 34              | 4     | 10    | 17    | 2,151515  |
| 38              | 4     | 8     | 19    | 2,243243  |
| 42              | 4     | 8     | 21    | 2,317073  |

Table 15. Examples of ideal graphs CHR5_e

To sum up, in the first group of analyzed graphs the best parameters have CHR5_b graphs. They possess minimal diameter and average path length in comparison to the other analyzed chordal rings, and the parameters of the real graphs are close or equal to parameters of ideal graphs. Additionally, most of the best graphs are symmetric, what is also an advantage for the application in real networks.

Fig. 16 shows the comparisons of the real graphs in the first group.

Fig. 16. Comparison of diameter and average path length of all real modified chordal rings belonging to the first group of analyzed graphs.

### 3.2 Second group of analyzed graphs

The chordal rings consisting of $4^i$ nodes ($i = 2, 3, 4, \ldots$) belong to this group. These topologies are often more complicated, since they are less symmetric. Basing on patterns for ideal and optimal graphs it is possible to derive expressions for average distance and diameter for all of the different topologies in this group of graphs.
Graph CHR5_f.

Definition 10. The modified fifth degree chordal ring called CHR5_f is denoted by CHR5_f(p; q_1, q_2, q_3, p/2), where p means the number of nodes and is positive and divisible by 4; q_1, q_2, q_3 are chords which possess even lengths less than p/2. The values of p/4 and q_1, q_2, q_3 must be prime each other. Each even node i_{2k} is connected to five other nodes: i_{2k-1}, i_{2k+1}, i_{2k+q_1(mod p)}, i_{2k-q_1(mod p)}, i_{2k+q_2(mod p)} while odd node i_{2k+1} is connected to i_{2k}, i_{2k+2}, i_{2k+1+q_2(mod p)}, i_{2k+1-q_2(mod p)} and i_{2k+1+q_2(mod p)} and node i_{2k+1} is connected to i_{2k}, i_{2k+2}, i_{2k+1+q_3(mod p)}, i_{2k+1-q_3(mod p)} and i_{2k+1+q_3(mod p)} where (0 ≤ k < p/2).

An example is shown in Fig. 17.

![Graph CHR5_f](image)

Fig. 17. Example of modified chordal ring CHR5_f(20; 4,6,8,10)

This structure is more complicated since the number of nodes appearing in successive layers depends on whether the total number of nodes is divisible by 8 or not, and also on whether it seen from odd or even node number in the graph. This creates multiple cases, which also complicates deriving the basic parameters. Table 16 shows the experimentally obtained results, which are the basis for further analysis.

| d         | Number of nodes | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|-----------|-----------------|---|---|---|---|---|---|---|---|
| p/4 p = 0 (mod 8) | Even           | 5 | 16 | 44 | 112 | 248 | 488 | 888 | 1496 |
|           | Odd            | 5 | 16 | 46 | 116 | 262 | 536 | 984 | 1640 |
| p/4 p ≠ 0 (mod 8) | Even           | 5 | 16 | 48 | 136 | 312 | 616 | 1096 | 1784 |
|           | Odd            | 5 | 18 | 58 | 152 | 340 | 668 | 1172 | 1884 |

Table 16. Maximal number of nodes in the successive layers

The number of nodes in the layers can be described by the following formula:

\[
\begin{align*}
\text{When } p = 0 \text{ (mod 8) and } d \text{ ) 5 then} \\
\quad p_{d, \text{even}} = \frac{5}{3} d^3 - 8d^2 - 173\frac{1}{3} + 664 \\
\quad p_{d, \text{odd}} = \frac{5}{3} d^3 - 8d^2 - 125\frac{1}{3} + 424 \\
\text{when } p \neq 0 \text{ (mod 8) and } d \text{ ) 4 then} \\
\quad p_{d, \text{even}} = \frac{1}{3} d^3 - 8d^2 - 93\frac{1}{3} + 312 \\
\quad p_{d, \text{odd}} = \frac{1}{3} d^3 - 8d^2 - 69\frac{1}{3} + 220
\end{align*}
\]

(39)
In Table 17 the total number of nodes in optimal graphs given by above expression is shown.

| $d(G)$ | Number of nodes | p = 0 (mod 8) | p ≠ 0 (mod 8) |
|--------|-----------------|---------------|---------------|
|        | even            | odd           | even          | odd           |
|        | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
| even   | 6   | 22  | 66  | 178 | 426 | 914 | 1802| 3298| 1   | 24  | 82  | 234 | 574 | 1242| 2414| 4298|
| odd    | 6   | 22  | 68  | 184 | 446 | 982 | 1966| 3606| 1   | 24  | 82  | 234 | 574 | 1242| 2414| 4298|

Table 17. Total numbers of nodes forming optimal graphs versus diameter

The total number of nodes $p_o$ in the optimal graph as a function of the diameter is given by:

$$p_o = \begin{cases} \frac{1}{3} D(G)^4 - \frac{89}{3} D(G)^2 + 576 D(G) - 1054, & \text{even, } p = 0 \text{ (mod 8)} \\ \frac{1}{3} D(G)^4 - \frac{65}{3} D(G)^2 + 360 D(G) - 554, & \text{odd, } p = 0 \text{ (mod 8)} \\ \frac{1}{3} D(G)^4 - \frac{49}{3} D(G)^2 + 264 D(G) - 402, & \text{even, } p \neq 0 \text{ (mod 8)} \\ \frac{1}{3} D(G)^4 - \frac{49}{3} D(G)^2 + 264 D(G) - 400, & \text{odd, } p \neq 0 \text{ (mod 8)} \end{cases}$$

The average path length in optimal graphs can be calculated using expressions:

$$d_{\text{avg}} = \begin{cases} \frac{6D(G)^4 + 4D(G)^3 - 18D(G)^2 - 16D(G) + 105}{8D(G)^3 - 32D(G) + 69}, & \text{even, } p = 0 \text{ (mod 8)} \\ \frac{6D(G)^4 + 4D(G)^3 - 6D(G)^2 - 4D(G) + 27}{8D(G)^3 - 8D(G) + 21}, & \text{odd, } p = 0 \text{ (mod 8)} \\ \frac{6D(G)^4 + 4D(G)^3 - 18D(G)^2 - 16D(G) + 105}{8D(G)^3 - 32D(G) + 69}, & \text{even, } p \neq 0 \text{ (mod 8)} \\ \frac{6D(G)^4 + 4D(G)^3 - 6D(G)^2 - 4D(G) + 27}{8D(G)^3 - 8D(G) + 21}, & \text{odd, } p \neq 0 \text{ (mod 8)} \end{cases}$$

Fig. 19 shows diameter and average path lengths in theoretical and real graphs with up to 100 nodes.

Fig. 18. Comparison of diameter and average path length of theoretical and real graphs CHR5_f
Analysis of Modified Fifth Degree Chordal Rings

Only three ideal graphs found, which is presented in Table 18.

| Number of nodes | $q_1$ | $q_2$ | $q_3$ | $p/2$ | $d_{av}$ |
|-----------------|-------|-------|-------|-------|---------|
| 12              | 2     | 4     | 4     | 6     | 1,545   |
| 20              | 6     | 4     | 4     | 10    | 1,737   |
| 32              | 6     | 12    | 12    | 16    | 2,161   |

Table 18. All found ideal graphs CHR5_f with up to 100 nodes.

Graph CHR5_g.

Definition 11. The modified fifth degree chordal ring called CHR5_g is denoted by CHR5_g($p; q_1, q_2, q_3$), where $p$ means the number of nodes, is positive and divisible by 4; $q_1$ is chord has odd length; $q_2, q_3$ are chords which possess even lengths and less then $p/2$. The values of $p$ and $q_1$ must be prime each other. Even node $i_{2k}$ is connected to $i_{2k-1}, i_{2k+1} (mod\ p), i_{2k+q_1 (mod\ p)}$ and $i_{2k+q_2 (mod\ p)}$ when $i_{2k}$ is in two (mod $p$) than this node is connected to $i_{2k+1}, i_{2k+1} (mod\ p), i_{2k+q_1 (mod\ p)}$ and $i_{2k+q_2 (mod\ p)}$ while odd node $i_{2k+1}$ is connected to $i_{2k}, i_{2k+2}, i_{2k+q_1 (mod\ p)}, i_{2k+q_2 (mod\ p)}$, $i_{2k+1+q_1 (mod\ p)}$ and any node $i_{2k+1} (mod\ p)$ is connected to $i_{2k}, i_{2k+2}, i_{2k+1+q_1 (mod\ p)}, i_{2k+1+q_2 (mod\ p)}$.

Fig. 19. Example of modified chordal ring CHR5_g(16; 3, 2, 6)

An example is shown in Fig. 20. The number of nodes in the layers of an optimal graph is given in Table 19.

| $d$ | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $p_{do}$ | 5   | 16  | 42  | 102 | 183 | 302 | 491 | 704 |

Table 19. Maximal number of nodes in the layers

In the case when the number of layer is bigger than 1, the number of nodes in the layers can be described by the following formula:

When $d = 0 \ (mod\ 3)$ then $p_{do} = \frac{4}{3} d^3 + \frac{8}{3} d - 2$

when $d = 1 \ (mod\ 3)$ and $d \geq 2$ then $p_{do} = \frac{4}{3} d^3 + \frac{2}{9} d^2 + \frac{29}{9} d + \frac{2}{9}$

when $d = 2 \ (mod\ 3)$ and $d \geq 4$ then $p_{do} = \frac{4}{3} d^3 - \frac{2}{9} d^2 + \frac{41}{9} d - \frac{8}{9}$

(42)
The total number of nodes $p_o$ in the optimal graph can be calculated using the expressions:

When $d = 0 \pmod{3}$ then $p_o = \frac{1}{3}D(G)^4 + \frac{2}{3}D(G)^3 + 2D(G)^2 + \frac{2}{3}D(G) - 1$

When $d = 1 \pmod{3}$ and $d \geq 2$ then $p_o = \frac{1}{3}D(G)^4 + \frac{2}{3}D(G)^3 + \frac{20}{9}D(G)^2 + \frac{5}{9}D(G) + \frac{2}{9}$ (43)

When $d = 2 \pmod{3}$ and $d \geq 2$ then $p_o = \frac{1}{3}D(G)^4 + \frac{2}{3}D(G)^3 + 2D(G)^2 + \frac{4}{3}D(G) + \frac{2}{3}$

In Table 20 the total number of nodes in optimal graphs described by formula given above is shown.

| $D(G)$ | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|
| $p_o$  | 6   | 22  | 64  | 166 | 349 | 651 | 1142| 1846|

Table 20. Diameters and total numbers of nodes in optimal graphs

The average path length in the optimal graphs as a function of its diameter can be calculated using equations (44).

When $D(G) = 0 \pmod{3}$

$$d_{av} = \frac{64,8 \left(D(G)\right)^5 + 54 \left(D(G)\right)^4 + 124 \left(D(G)\right)^3 - 10 \left(D(G)\right)^2 - 47 D(G) - 4}{1 \left(D(G)\right)^4 + 2 \left(D(G)\right)^3 + 2 \left(D(G)\right)^2 + \frac{2}{9} D(G) - 2}$$

When $D(G) = 1 \pmod{3}$

$$d_{av} = \frac{64,8 \left(D(G) - 1\right)^5 - 54 \left(D(G) - 1\right)^4 + 124 \left(D(G) - 1\right)^3 - 14 \left(D(G) - 1\right)^2}{\frac{1}{3} \left(D(G) - 1\right)^4 + \frac{2}{3} \left(D(G) - 1\right)^3 + \frac{20}{9} \left(D(G) - 1\right)^2 + \frac{5}{27} \left(D(G) - 1\right) - \frac{7}{9}}$$

When $D(G) = 2 \pmod{3}$

$$d_{av} = \frac{64,8 \left(D(G) - 2\right)^5 + 162 \left(D(G) - 2\right)^4 + 574 \left(D(G) - 2\right)^3 + 117 \left(D(G) - 2\right)^2}{\frac{1}{3} \left(D(G) - 2\right)^4 + \frac{2}{3} \left(D(G) - 2\right)^3 + \frac{2}{9} \left(D(G) - 2\right)^2 + \frac{4}{9} \left(D(G) - 2\right) - \frac{1}{3}}$$

(44)
Fig. 20 shows diameter and average path lengths in theoretical and real graphs with up to 100 nodes.

Fig. 20. Comparison of diameter and average path length of theoretical and real graphs

CHR5_g

Graph CHR5_h.

Definition 12. The modified fifth degree chordal ring called CHR5_h is denoted by

CHR5_h(p; q_1,q_2,q_3,q_4,q_5),

where p means the number of nodes and is positive and divisible by 4; q_1, q_2, q_3, q_4, q_5 are chords which possess even lengths less then \( p/2 \), \( q_5=p/2 \). Even node \( i_{2k} \) is connected to five other nodes: \( i_{2k-1} \), \( i_{2k+1} \), \( i_{2k+q_1(\text{mod } p)} \) and to \( i_{2k+q_1(\text{mod } p)} \) when number of node is equal to 0 mod 4 or to \( i_{2k+q_2(\text{mod } p)} \). \( i_{2k+q_2(\text{mod } p)} \) when number of node is equal to 2 mod 4, while odd node \( i_{2k+1} \) is connected to \( i_{2k+2} \), \( i_{2k+1+q_3(\text{mod } p)} \) and \( i_{2k+1+q_3(\text{mod } p)} \) when number of node is equal to 1 mod 4 or to \( i_{2k+1+q_4(\text{mod } p)} \). \( i_{2k+1+q_4(\text{mod } p)} \) when number of node is equal to 3 mod 4.

An example is shown in Fig. 21, and the number of nodes in the layers of an optimal graph is shown in tables 21 and 22.

Fig. 21. Example of modified chordal ring CHR5_h(20; 4,4,8,8,10)

| \( d \) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|-------|---|---|---|---|---|---|---|---|
| \( p_{do} \) | 5 | 18 | 64 | 196 | 524 | 1244 | 2636 | 5068 |

Table 21. The number of nodes appearing in layers when \( p \) is not divided by 8

| \( d \) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|-------|---|---|---|---|---|---|---|---|
| \( p_{do} \) | 5 | 16 | 48 | 136 | 358 | 868 | 1908 | 3804 |

Table 22. The number of nodes appearing in layers when \( p \) is divided by 8
The number of nodes in the layers, as shown in Tables 21 and 22, can be described by the following expression:

\[
\begin{align*}
\text{When } & \quad d > 5 \text{ and } p \text{ is not divisible by } 8 \text{ then} \\
& \quad p_{d,e} = \frac{8}{3} d^4 - \frac{16}{3} d^3 + 154\frac{2}{3} d^2 + 1133\frac{8}{3} d - 2292 \\
\text{when } & \quad d > 7 \text{ and } p \text{ is divisible by } 8 \text{ then} \\
& \quad p_{d,e} = \frac{8}{3} d^4 - \frac{16}{3} d^3 - 154\frac{2}{3} d^2 + 1133\frac{8}{3} d - 2292
\end{align*}
\]  

In Table 23 the total number of nodes in optimal graphs described by expression given above is shown.

| \( D(G) \) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|------------|---|---|---|---|---|---|---|---|
| \( p_e \) is not divisible by 8 | 6 | 24 | 88 | 284 | 808 | 2052 | 4688 | 9756 |
| \( p_e \) is divisible by 8 | 6 | 22 | 70 | 206 | 564 | 1432 | 3340 | 7144 |

Table 23. Total numbers of nodes forming optimal graphs versus diameter

The average path length in optimal graphs:

\[
\begin{align*}
\text{When } & \quad D(G) > 4 \text{ and } p \text{ is not divisible by } 8 \text{ then} \\
& \quad d_{avo} = \frac{4}{9} D(G)^6 + \frac{4}{15} D(G)^5 + \frac{40}{9} D(G)^4 - \frac{40}{3} D(G)^3 + 298\frac{2}{3} D(G)^2 - 618\frac{2}{9} D(G) - 956\frac{14}{15} D(G)
\end{align*}
\]  

When \( D(G) > 4 \) and \( p \) is divisible by 8

\[
\begin{align*}
& \quad d_{avo} = \frac{8}{15} D(G)^5 - \frac{160}{3} D(G)^3 + 488d^2 + 1751\frac{4}{5} d + 2363 \\
& \quad + \frac{8}{27} D(G)^5 - \frac{272}{3} D(G)^3 - 1008\frac{2}{3} D(G)^2 + 4505\frac{13}{15} D(G) + 7624
\end{align*}
\]  

\[
\begin{align*}
& \quad d_{avo} = \frac{4}{9} D(G)^6 + \frac{4}{15} D(G)^5 + \frac{40}{9} D(G)^4 - \frac{40}{3} D(G)^3 + 298\frac{2}{3} D(G)^2 - 618\frac{2}{9} D(G) - 956\frac{14}{15} D(G)
\end{align*}
\]  

When \( D(G) > 4 \) and \( p \) is divisible by 8

\[
\begin{align*}
& \quad d_{avo} = \frac{8}{15} D(G)^5 - \frac{160}{3} D(G)^3 + 488d^2 + 1751\frac{4}{5} d + 2363 \\
& \quad + \frac{8}{27} D(G)^5 - \frac{272}{3} D(G)^3 - 1008\frac{2}{3} D(G)^2 + 4505\frac{13}{15} D(G) + 7624
\end{align*}
\]  

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Fig. 22. Comparison of diameter and average path length of theoretical and real graphs CHR5_h

Fig. 22 shows diameter and average path lengths in theoretical and real graphs with up to 100 nodes.

There are only three chordal rings which possess basic parameters equal to parameters of theoretical graphs: These are: CHR5_h(12; 4,4,4,4,6), CHR5_h(40; 4,12,4,12,20) and CHR5_h(44; 4,8,12,16,22).

Graph CHR5_i.

Definition 13. The modified fifth degree chordal ring called CHR5_i is denoted by CHR5_i(p; q_1,q_2,q_3,q_4), where p means the number of nodes and is positive and divisible by 4; q_1, q_2, q_3, q_4 are chords which possess: q_1 - odd length and q_2, q_3, q_4 - even lengths less then p/2. Each node is connected to five other nodes. Even node i_2k is connected to i_{2k-1}, i_{2k+1}, i_{2k+q_1(mod p)}, i_{2k+q_1(mod p)} and i_{2k+q_2(mod p)}. While odd node i_{2k+1} is connected to i_{2k}, i_{2k+2}. i_{2k+q_2(mod p)}, i_{2k+1+q_3(mod p)}, i_{2k+1+q_3(mod p)} and odd node i_{2k+1} is connected to i_{2k}, i_{2k+2}, i_{2k+1+q_2(mod p)}, i_{2k+1+q_3(mod p)}, i_{2k+1-q_4(mod p)}.

Fig. 23. Example of modified chordal ring CHR5_i(20; 5,6,4,8)

An example of a CHR5_i is shown in Fig. 23. The distribution of nodes in the layers depends on whether the graph is seen from odd or even node in Table 24 is given.

| d   | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | Node number |
|-----|----|----|----|----|----|----|----|----|-------------|
| p_{10} | 5  | 20 | 63 | 190| 465| 1010| 2001| 3594| even        |
| p_{10} | 5  | 20 | 69 | 196| 493| 1094| 2141| 3790| odd         |

Table 24. Maximal number of nodes in the layers
The distribution of nodes in the layers can be described by the expression:

\[
\begin{align*}
&\text{When } d > 4 \text{ and node number is even} \\
p_{d\text{even}} &= d^4 + 6d^2 - 192d + 650 \\
&\text{when } d > 4 \text{ and node number is odd} \\
p_{d\text{odd}} &= d^4 + 6d^2 - 136d + 398
\end{align*}
\]

The total number of nodes in optimal graphs calculated depending on the source node number, given in Table 25, can be expressed as follows:

\[
\begin{align*}
&\text{When } D(G) > 3 \text{ and node number is even} \\
p_{o\text{even}} &= \frac{D(G)^5}{5} + \frac{D(G)^4}{2} + \frac{7}{3}D(G)^3 - 93D(G)^2 + \frac{554}{30}D(G) - 935 \\
&\text{when } D(G) > 3 \text{ and node number is odd} \\
p_{o\text{odd}} &= \frac{D(G)^5}{5} + \frac{D(G)^4}{2} + \frac{7}{3}D(G)^3 - 65D(G)^2 + \frac{330}{30}D(G) - 475
\end{align*}
\]

| \(D(G)\) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | Node number |
|---|---|---|---|---|---|---|---|---|-------------|
| \(p_o\) | 6 | 26 | 89 | 279 | 744 | 1754 | 3755 | 7349 | even |
| | 6 | 26 | 95 | 291 | 784 | 1878 | 4019 | 7809 | odd |

Table 25. Total numbers of nodes in the optimal graphs

The average path length in optimal graphs is equal to:

\[
d_{av\text{even}} = \frac{d_{\text{even even}} + d_{\text{even odd}}}{2} = \frac{D(G)^6 + \frac{D(G)^5}{2} + \frac{11}{12}D(G)^4 - \frac{42}{3}D(G)^3 + 132\frac{5}{12}D(G)^2 + 176\frac{1}{3}D(G) - 764}{2\left(\frac{D(G)^5}{5} + \frac{D(G)^4}{2} + \frac{7}{3}D(G)^3 - 93D(G)^2 + \frac{554}{30}D(G) - 936\right)} + \frac{D(G)^6 + \frac{D(G)^5}{2} + \frac{11}{12}D(G)^4 - \frac{61}{3}D(G)^3 + 230\frac{5}{12}D(G)^2 + 293D(G) - 1646}{2\left(\frac{D(G)^5}{5} + \frac{D(G)^4}{2} + \frac{7}{3}D(G)^3 - 65D(G)^2 + \frac{330}{30}D(G) - 476\right)}
\]

Fig. 24. Comparison of diameter and average path length of theoretical and real graphs CHR5_i
Analysis of Modified Fifth Degree Chordal Rings

Fig. 24 shows diameter and average path lengths in theoretical and real graphs with up to 100 nodes.

For graphs with less than 72 nodes it is possible to find real graphs with parameters close to those of ideal graphs. However the difference becomes bigger for larger graphs. The differences seem to come from the different path lengths calculated from odd and even nodes. The ideal graphs found are shown in table 26.

| Number of nodes | \(q_1\) | \(q_2\) | \(q_3\) | \(q_4\) | \(d_{av}\) |
|-----------------|--------|--------|--------|--------|---------|
| 12              | 5      | 2      | 4      | 4      | 1,545   |
| 16              | 7      | 2      | 4      | 4      | 1,667   |
| 36              | 13     | 10     | 16     | 16     | 2,143   |
| 40              | 9      | 6      | 12     | 12     | 2,231   |
| 44              | 9      | 6      | 12     | 20     | 2,302   |
| 48              | 5      | 10     | 20     | 20     | 2,362   |
| 52              | 5      | 10     | 20     | 20     | 2,412   |

Table 26. Ideal graphs CHR5_i

**Graph CHR5. j**

Definition 14. The modified fifth degree chordal ring called CHR5. j is denoted by CHR5. j(\(p; q_1,q_2,q_3,q_4\)), where \(p\) is the number of nodes. It must be positive and divisible by 4. Chords \(q_1\) and \(q_2\) have odd lengths; \(q_3\) and \(q_4\) possess even lengths, all chords lengths are less than \(p/2\).

Each node is connected to five other nodes. Even nodes \(i_{2k}\) are connected to \(i_{2k-1}, i_{2k+1}\) and to \(i_{2k+q_1(mod \ p)}\), \(i_{2k+q_2(mod \ p)}\) and \(i_{2k+q_3(mod \ p)}\) when \(2k = 0 (mod 4)\) or to \(i_{2k-q_2(mod \ p)}\) when \(2k = 2 (mod 4)\); while odd nodes \(i_{2k+1}\) are connected to \(i_{2k}, i_{2k+2}, i_{2k+1+q_3(mod \ p)}, i_{2k+1+q_1(mod \ p)}\) and to \(i_{2k+1+q_4(mod \ p)}\) when \(2k+1=1 (mod 4)\) or to \(i_{2k+1-q_4(mod \ p)}\) when \(2k+1 = 3 (mod 4)\).

Fig. 25. Example of modified chordal ring CHR5. j(20; 3,9,2,6)

Based on going through all the real graphs, the distribution of nodes in the layers of CHR5. j is as follows (Table 27):

| \(d\) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|-------|---|---|---|---|---|---|---|---|
| \(p_{do}\) | 5 | 20 | 62 | 174 | 375 | 718 | 1303 | 2136 |

Table 27. Maximal number of nodes in the successive layers

The distribution of nodes in the layers of an optimal graph is described by expression:

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When \( d \) 2 and \( d = 0 \) (mod 3) then
\[
p_{do} = \frac{77}{162} \left( \frac{d}{3} \right)^4 + 27 \frac{1}{2} \left( \frac{d}{3} \right)^2 - 4
\]
when \( d \) 2 and \( d = 1 \) (mod 3) then
\[
p_{do} = \frac{77}{162} \left( \frac{d-1}{3} \right)^4 + 52 \frac{1}{2} \left( \frac{d-1}{3} \right)^3 + 53 \frac{1}{2} \left( \frac{d-1}{3} \right)^2 + 24 \frac{2}{3} \left( \frac{d-1}{3} \right)^4 + 5
\]
when \( d \) 2 and \( d = 2 \) (mod 3) then
\[
p_{do} = \frac{77}{162} \left( \frac{d-2}{3} \right)^4 + 101 \frac{2}{3} \left( \frac{d-2}{3} \right)^3 + 129 \frac{1}{2} \left( \frac{d-2}{3} \right)^2 + 83 \frac{1}{3} \left( \frac{d-2}{3} \right)^2 + 22
\]

In Table 28 the total number of nodes in virtual, optimal graphs is shown as function of diameter.

| \( d(G) \) | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|
| \( p_{do} \) | 6   | 26  | 88  | 262 | 637 | 1355| 2658| 4794|

Table 28. Total numbers of nodes in optimal graphs versus diameter

The total number of nodes in optimal graphs calculated as a function of its diameter can be expressed as follows:

When \( D(G) \) 2 and \( D(G) = 0 \) (mod 3) then
\[
p_o = \frac{23}{10} \left( \frac{D(G)}{3} \right)^5 + 19 \frac{1}{4} \left( \frac{D(G)}{3} \right)^4 + 31 \frac{2}{3} \left( \frac{D(G)}{3} \right)^3 + \\
+ 12 \frac{3}{4} \left( \frac{D(G)}{3} \right)^2 + 2 \frac{7}{30} \left( \frac{D(G)}{3} \right) - 1
\]
when \( D(G) \) 2 and \( D(G) = 1 \) (mod 3) then
\[
p_o = \frac{23}{10} \left( \frac{D(G)-1}{3} \right)^5 + 57 \frac{3}{4} \left( \frac{D(G)-1}{3} \right)^4 + 84 \frac{2}{3} \left( \frac{D(G)-1}{3} \right)^3 + \\
+ 66 \frac{1}{4} \left( \frac{D(G)-1}{3} \right)^2 + 26 \frac{8}{9} \left( \frac{D(G)-1}{3} \right) + 4
\]
when \( D(G) \) 2 and \( D(G) = 2 \) (mod 3) then
\[
p_o = \frac{23}{10} \left( \frac{D(G)-2}{3} \right)^5 + 96 \frac{1}{4} \left( \frac{D(G)-2}{3} \right)^4 + 185 \frac{2}{3} \left( \frac{D(G)-2}{3} \right)^3 + \\
+ 195 \frac{3}{4} \left( \frac{D(G)-2}{3} \right)^2 + 110 \frac{7}{30} \left( \frac{D(G)-2}{3} \right) + 26
\]

The average path length in optimal graphs is described by (53):
When $D(G) \not\equiv 2$ and $D(G) = 0 \pmod{3}$ then

$$d_{avv} = \frac{57}{4} \left( \frac{D(G)}{3} \right)^6 + \frac{57}{4} \left( \frac{D(G)}{3} \right)^5 + \frac{77}{12} \left( \frac{D(G)}{3} \right)^4 +$$

$$+ \frac{39}{12} \left( \frac{D(G)}{3} \right)^3 + 4 \frac{251}{300} \left( \frac{D(G)}{3} \right)^2 - 2 \frac{101}{300} \left( \frac{D(G)}{3} \right) - 4$$

when $D(G) \equiv 2$ and $D(G) = 1 \pmod{3}$ then

$$d_{avv} = \frac{57}{4} \left( \frac{D(G)-1}{3} \right)^6 - \frac{173}{4} \left( \frac{D(G)-1}{3} \right)^5 + \frac{277}{12} \left( \frac{D(G)-1}{3} \right)^4 +$$

$$- \frac{261}{4} \left( \frac{D(G)-1}{3} \right)^3 + 146 \frac{1}{3} \left( \frac{D(G)-1}{3} \right)^2 - 42 \left( \frac{D(G)-1}{3} \right) + 1$$

when $D(G) \equiv 2$ and $D(G) = 2 \pmod{3}$ then

$$d_{avv} = \frac{57}{4} \left( \frac{D(G)}{3} \right)^6 - \frac{57}{4} \left( \frac{D(G)}{3} \right)^5 + \frac{77}{12} \left( \frac{D(G)}{3} \right)^4 +$$

$$- \frac{42}{12} \left( \frac{D(G)}{3} \right)^3 + 16 \frac{5}{6} \left( \frac{D(G)}{3} \right)^2 - 2 \frac{1}{3} \left( \frac{D(G)}{3} \right) - 4$$

(53)

Fig. 27 shows diameter and average path lengths in theoretical and real graphs with up to 100 nodes.

Fig. 26. Comparison of diameter and average path length of theoretical and real graphs CHR5_j

There are a few graphs having values of basic parameters equal to those of ideal graphs. For example: CHR5_j(44; 5,17,14,22), CHR5_j(48; 5,17,14,22), CHR5_j(52; 5,15,18,26), CHR5_j(56; 7,19,10,22).

Among all graphs belonging to the second group the best parameters (minimal diameter and minimal average path length given the number of nodes) were found in CHR5_i but other in minimal degree are slightly different it (especially from CHR5_j). In Fig. 27 the comparison of the second group of graphs is shown.

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3.3 Analysed graphs – Third group

There are a number of other topologies, for which we have not found any nice expressions for the distribution of nodes in layers, and thus no expressions of the average distance and diameter could be derived. Due to the good basic parameters the topologies have been described, but further research is needed in order to provide more precise descriptions.

Graph CHR5_k.

Definition 15. The modified fifth degree chordal ring called CHR5_k is denoted by CHR5_k(p; q_1,q_2,q_3,q_4,q_5,q_6), where p is the number of nodes. It must be positive and divisible by 4. All chords have even lengths less than p/2. Each node is connected to five other nodes. Even nodes i_{2k} are connected to i_{2k-1}, i_{2k+1} and to i_{2k+q_1(mod p)}, i_{2k+q_5(mod p)} when 2k = 0 (mod4) or to i_{2k+q_2(mod p)}, i_{2k+q_6(mod p)} when 2k = 2 (mod4); while odd nodes i_{2k+1} are connected to i_{2k}, i_{2k+2} and to i_{2k+1+q_3(mod p)}, i_{2k+1+q_6(mod p)} when 2k+1 = 1 (mod4) or to i_{2k+1+q_4(mod p)}, i_{2k+1+q_6(mod p)} when 2k+1 = 3 (mod4).

An example is shown in Fig. 28.
Using the results shown in Table 29, the counted total number of nodes in virtual optimal graphs is presented in Table 30.

| $D(G)$ | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|--------|----|----|----|----|----|----|----|----|
| $p_0$  | 6  | 26 | 106| 390| 1285| 3805| 10138| 24472|

Table 30. Total numbers of nodes forming optimal graphs versus diameter

In Fig. 29 comparison of diameter and average path length of theoretical and real graphs $CHR5_k$ is shown.

Only three graphs with average distance and diameter equal to those of ideal graphs can be found. These are $CHR5_k(12; 4,4,4,2,6), CHR5_k(44; 4,8,12,16,22), CHR5_k(52; 4,8,12,16,22,26)$.

**Graph $CHR5_1$.**

Definition 16. The modified fifth degree chordal ring called $CHR5_1$ is denoted by $CHR5_1(p_1, q_1, q_2, q_3, q_4, q_5)$, where $p_1$ means the number of nodes and is positive and divisible by 4. Chord $q_1$ has odd length, other chords have even length. The lengths of all chords are less than $p_1/2$.

Each node is connected to five other nodes. Even nodes $i_2k$ are connected to $i_2k+1, i_2k+2, i_2k+3, i_2k+4, i_2k+5$ when $2k = 0 \pmod{4}$ or to $i_2k+1, i_2k+2, i_2k+3, i_2k+4, i_2k+5$ when $2k+1 = 1 \pmod{4}$ or to $i_2k+1, i_2k+2, i_2k+3, i_2k+4, i_2k+5$ when $2k+2 = 2 \pmod{4}$; while odd nodes $i_2k+1$ are connected to $i_2k+2, i_2k+3, i_2k+4, i_2k+5, i_2k+6$ when $2k+1 = 2 \pmod{4}$ or to $i_2k+1, i_2k+2, i_2k+3, i_2k+4, i_2k+5$ when $2k+2 = 3 \pmod{4}$.

An example is shown in Fig. 30.

Fig. 30. Example of modified chordal ring $CHR5_1(16; 7,6,2,2,6)$

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In Table 31 the distribution of nodes in the layers is shown.

| $d$ | $p_{do}$ |
|-----|---------|
| 1   | 5       |
| 2   | 20      |
| 3   | 71      |
| 4   | 228     |
| 5   | 555     |
| 6   | 1216    |
| 7   | 2442    |
| 8   | 4458    |

Table 31. Maximal number of nodes in the successive layers

Using the results shown in Table 31, the total number of nodes in virtual optimal graphs calculated in this way was presented in Table 32.

| $D(G)$ | $p_o$ |
|--------|-------|
| 1      | 6     |
| 2      | 26    |
| 3      | 97    |
| 4      | 325   |
| 5      | 880   |
| 6      | 2096  |
| 7      | 4538  |
| 8      | 8996  |

Table 32. Total numbers of nodes forming optimal graphs versus diameter

In Fig. 31 comparison of diameter and average path length of theoretical and real graphs CHR5_l is shown.

Examples of ideal graphs include: CHR5_l(16; 3,2,2,6,6), CHR5_l(44; 11,6,14,22,18), CHR5_l(48; 7,10,18,14,22), CHR5_l(52; 11,6,18,26,22), CHR5_l(56; 11,14,6,22,26).

Graph CHR5_m.

Definition 17. The modified fifth degree chordal ring called CHR5_m is denoted by

CHR5_m$(p; q_1,q_2,q_3,q_4)$, where $p$ means the number of nodes and is positive and divisible by 4. All chords have even length less than $p/2$. Each node is connected to five other nodes. Even nodes $i_{2k}$ are connected to $i_{2k+1}$, $i_{2k+1+q_1(mod p)}$, $i_{2k+q_2(mod p)}$ and to $i_{2k+q_2(mod p)}$ when $2k = 0 (mod 4)$ or to $i_{2k+q_2(mod p)}$ when $2k = 2 (mod 4)$; while odd nodes $i_{2k+1}$ are connected to $i_{2k}$, $i_{2k+2}$, $i_{2k+1+q_3(mod p)}$, $i_{2k+1+q_3(mod p)}$ and to $i_{2k+1+q_4(mod p)}$ when $2k+1 = 1 (mod 4)$ or to $i_{2k+1+q_4(mod p)}$ when $2k+1 = 3 (mod 4)$.
Analysis of Modified Fifth Degree Chordal Rings

Fig. 32. Example of modified chordal ring $CHR5_m(16; 2,6,6,2)$

An example of $CHR5_m$ is given in Fig. 32.

In Table 33 the distribution of nodes in layers is shown. The total number of nodes in optimal graphs, calculated based on these results, are shown in Table 34.

| $d$ | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|-----|----|----|----|----|----|----|----|----|
| $p_{do}$ | 5  | 20 | 71 | 210| 511| 1064| 1997| 3440|

Table 33. Maximal number of nodes in the layers

| $D(G)$ | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|--------|----|----|----|----|----|----|----|----|
| $p_o$  | 6  | 26 | 97 | 307| 818| 1882| 3879| 7319|

Table 34. Total numbers of nodes forming optimal graphs versus diameter

In Fig. 34 comparison of diameter and average path length of theoretical and real graphs $CHR5_m$ is shown.

Examples of ideal chordal rings with up to 100 nodes include: $CHR5_m(12; 2,2,6,6)$, $CHR5_m(40; 6,14,10,18)$, $CHR5_m(44; 6,14,10,18)$, $CHR5_m(48; 10,22,6,14)$, $CHR5_m(56; 18,26,14,6)$, $CHR5_m(40; 6,14,10,18)$.

Graph $CHR5_n$.

Definition 18. The modified fifth degree chordal ring called $CHR5_n$ is denoted by $CHR5_n(p; q_1,q_2,q_3,q_4,q_5,q_6)$, where $p$ means the number of nodes and is positive and divisible
by 4. All chords have even length less than $p/2$. Each node is connected to five other nodes. Even nodes $i_{2k}$ are connected to $i_{2k+1}, i_{2k+1}$ and to $i_{2k+q_1}\text{mod} \ p, i_{2k+q_2}\text{mod} \ p, i_{2k+q_3}\text{mod} \ p$ when $2k = 0 \pmod{4}$ or to $i_{2k+q_1}\text{mod} \ p, i_{2k+q_2}\text{mod} \ p, i_{2k+q_3}\text{mod} \ p$ when $2k = 2 \pmod{4}$; while odd nodes $i_{2k+1}$ are connected to $i_{2k}, i_{2k+2}$ and to $i_{2k+1+q_1}\text{mod} \ p, i_{2k+1+q_2}\text{mod} \ p, i_{2k+1+q_3}\text{mod} \ p$ when $2k+1 = 1 \pmod{4}$ or to $i_{2k+1+q_1}\text{mod} \ p, i_{2k+1+q_2}\text{mod} \ p, i_{2k+1+q_3}\text{mod} \ p$ when $2k+1 = 3 \pmod{4}$.

An example of a CHR5_n graph is shown in Fig. 34.

Fig. 34. Example of modified chordal ring CHR5_n(20; 2,6,10,2,6,10)

In Table 35 the distribution of nodes in layers is presented.

| $d$ | $p_{do}$ |
|-----|----------|
| 1   | 5        |
| 2   | 20       |
| 3   | 77       |
| 4   | 272      |
| 5   | 764      |
| 6   | 1916     |
| 7   | 4268     |
| 8   | 8696     |

Table 35. Maximal number of nodes in the layers

The total number of nodes in optimal graphs calculated based on the results given in Table 35 is shown in Table 36.

| $D(G)$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|--------|---|---|---|---|---|---|---|---|
| $p_{o}$ | 6 | 26 | 103 | 375 | 1139 | 3055 | 7323 | 16019 |

Table 36. Total numbers of nodes in optimal graphs as a function of the diameter

In Fig. 36 shows the comparison of diameter and average path length of theoretical and real graphs CHR5_n.

Fig. 35. Comparison of diameter and average path length of theoretical and real graphs CHR5_n
Going through all nodes with up to 100 nodes only one ideal graph was found, namely CHR5_n(52; 10,6,14,18,26,22) with 52 nodes.

**Graph CHR5_o.**

Definition 19. The modified fifth degree chordal ring called CHR5_o is denoted by CHR5_o(p; q_1,q_2,q_3,q_4,q_5) where p means the number of nodes and is positive and divisible by 4. All chords have even length less than (p/2+1). Each node is connected to five other nodes. Even nodes \(i_{2k}\) are connected to \(i_{2k+1}\), \(i_{2k+1}\) and to \(i_{2k+q_1\bmod p}\), \(i_{2k+q_1\bmod p}\) when \(2k = 0 \pmod{4}\) or to \(i_{2k-q_1\bmod p}\) when \(2k = 2 \pmod{4}\); while odd nodes \(i_{2k+1}\) are connected to \(i_{2k}, i_{2k+2}, i_{2k+1+q_2\bmod p}\) and to \(i_{2k+1+q_3\bmod p}\), \(i_{2k+1+q_3\bmod p}\) when \(2k+1 = 1 \pmod{4}\) or to \(i_{2k+1+q_4\bmod p}\), \(i_{2k+1+q_4\bmod p}\) when \(2k+1 = 3 \pmod{4}\).

An example of a CHR5_o graph is shown in Fig. 36.

![Fig. 36. Example of modified chordal ring CHR5_o(20; 6,2,4,8,10)](image)

In Table 37 the distribution of nodes in layers is shown. Based on these numbers Table 38 is derived, showing the numbers of nodes in optimal graphs as a function of the diameter.

| d   | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | Node number |
|-----|----|----|----|----|----|----|----|----|-------------|
| p_o | 5  | 20 | 73 | 244| 699| 1726| 3779| 7498| even        |
|     | 5  | 20 | 78 | 254| 719| 1778| 3893| 7696| odd         |

Table 37. Maximal number of nodes in the layers

| d(G) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | Node number |
|------|----|----|----|----|----|----|----|----|-------------|
| p_o  | 6  | 26 | 99 | 343| 1042| 2768| 6547| 14045| even        |
|      | 6  | 26 | 104| 358| 1077| 2855| 6748| 14444| odd         |

Table 38. Total numbers of nodes forming optimal graphs versus diameter

A number of ideal graphs can be found, such as CHR5_o(12; 6,2,4,4,4), CHR5_o(16; 2,6,6,4,4), CHR5_o(20; 10,10,6,4,4), CHR5_o(36; 10,18,14,4,8), CHR5_o(44; 6,14,10,20,4), CHR5_o(52; 6,10,14,20,24).

Fig. 37 shows the comparison of diameter and average path length of theoretical and real CHR5_o graphs.
Fig. 37. Comparison of diameter and average path length of theoretical and real graphs
CHR5_o

As for the previous group of graphs, the chordal rings of this group are compared with respect to the basic parameters. The comparison is given in Fig. 38.

Fig. 38. Comparison of basic parameters of analyzing group chordal rings

From Fig. 38 it follows that all graphs belonging to third group of chordal rings have very similar properties when the number of nodes is smaller than 100.

4. Analysis of obtained results

Based on the obtained results for all 15 groups of graphs presented, the values of minimum diameter and average path lengths can be compared. Despite the differences found between theoretical and real parameters the comparisons will be based on the theoretical values.

First, Fig. 39 presents the average path lengths as a function of the diameter in the graphs. This does not take into account the number of nodes in the graphs, which vary significantly between the different graphs as can be seen in Table 39 and Fig. 40. It can be seen that for a given number of nodes, CHR5_k has the smallest diameter.

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Fig. 39. Comparison of the calculated average paths length in the function of the diameter of graphs

Fig. 40. Relationship between the total number of nodes and diameters

In the following section, a comparison of the average path length as a function of the number of nodes is presented. In order to compare graphs with different numbers of nodes, a “Normalized estimator of average path length” \( E_{\text{nav}} \) is introduced as follows:

\[
E_{\text{nav}} = \frac{\sum_{d=1}^{D(G)} d_{avD(G)} P_{dr}}{\sum_{d=1}^{d_{avD(G)}} d P_d} \quad (54)
\]

Where \( d_{avD(G)} \) means the average path length of a particular graph when its diameter is equal to \( D(G) \), and \( d_{avD(G)} \) means the average path length of the reference graph, \( \sum_{d=1}^{d(G)} P_{dr} \) is the total number of nodes in relation graph, \( \sum_{d=1}^{d(G)} P_d \) - total number of nodes in the particular graph.

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| Graph   | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|---------|----|----|----|----|----|----|----|----|----|----|
| CHR5    | 6  | 18 | 38 | 66 | 102| 146| 198| 258| 326| 402|
| CHR5_a  | 6  | 22 | 55 | 113| 202| 330| 503| 729| 1014|1366|
| CHR5_b  | 6  | 26 | 87 | 227| 494| 948| 1661|2717| 4212|6254|
| CHR5_c  | 6  | 26 | 76 | 186| 386| 726| 1276|2126| 3386|5186|
| CHR5_d  | 6  | 23 | 61 | 130| 239| 400| 622 |915 | 1288|1753|
| CHR5_e  | 6  | 23 | 68 | 160| 316| 552| 884 |1328| 1900|2616|
| CHR5_f  | 6  | 23 | 72 | 201| 491| 1068|2103| 3804|6411 |10196|
| CHR5_g  | 6  | 22 | 64 | 166| 349| 651 |1142| 1846|2840 |4228|
| CHR5_h  | 6  | 23 | 79 | 245| 686| 1742|4014| 8450|16430|29842|
| CHR5_i  | 6  | 26 | 92 | 285| 764| 1816|3887 |7579| 13674|23158|
| CHR5_j  | 6  | 26 | 88 | 262| 637| 1355|2658 |4794| 8148 |13240|
| CHR5_k  | 6  | 26 | 106| 390| 1285|3805 |10138|24472|54108|110878|
| CHR5_l  | 6  | 26 | 97 | 325| 880| 2096|4538 |8996| 16706|29420|
| CHR5_m  | 6  | 26 | 97 | 307| 818| 1882|3879 |7319| 12876|21406|
| CHR5_n  | 6  | 26 | 103| 375| 1139|3055 |7323| 16019|32520|62092|
| CHR5_o  | 6  | 26 | 102| 351| 1060|2812 |6648| 14245|28120|51864|

Table 39. Total number of nodes versus diameters.

The results are shown in Table 40 and Fig. 41.

Fig. 41. Distribution of the normalized estimator of average path length versus graph diameter.

From Fig. 41 it can be seen that the CHR5_k has the relatively shortest average path length. Not surprisingly, the distributions of the number of nodes in the layers have a great impact on the two basic parameters. This can be seen also from expressions (7) and (9). The difference in the distribution for all graphs is shown in Fig. 42.

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Table 40. Distribution of the normalized estimator of the average path length versus the graph diameter

| Graph | 1   | 2    | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-------|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| CHR5  | 1,000 | 0.948 | 0.886 | 0.840 | 0.807 | 0.785 | 0.768 | 0.756 | 0.746 | 0.738 | 0.732 | 0.726 |
| CHR5_a| 1,000 | 0.979 | 0.928 | 0.892 | 0.866 | 0.848 | 0.834 | 0.824 | 0.816 | 0.810 | 0.804 | 0.800 |
| CHR5_b| 1,000 | 1,000 | 0.977 | 0.947 | 0.922 | 0.903 | 0.889 | 0.878 | 0.870 | 0.863 | 0.857 | 0.853 |
| CHR5_c| 1,000 | 1,000 | 0.958 | 0.932 | 0.909 | 0.894 | 0.885 | 0.879 | 0.875 | 0.871 | 0.868 | 0.865 |
| CHR5_d| 1,000 | 0.985 | 0.938 | 0.903 | 0.877 | 0.858 | 0.844 | 0.833 | 0.824 | 0.818 | 0.811 | 0.806 |
| CHR5_e| 1,000 | 0.985 | 0.957 | 0.926 | 0.898 | 0.877 | 0.860 | 0.847 | 0.836 | 0.828 | 0.820 | 0.814 |
| CHR5_f| 1,000 | 0.982 | 0.967 | 0.954 | 0.941 | 0.928 | 0.918 | 0.908 | 0.899 | 0.891 | 0.883 | 0.876 |
| CHR5_g| 1,000 | 0.979 | 0.953 | 0.940 | 0.914 | 0.895 | 0.885 | 0.874 | 0.866 | 0.861 | 0.855 | 0.851 |
| CHR5_h| 1,000 | 0.985 | 0.978 | 0.969 | 0.961 | 0.954 | 0.946 | 0.939 | 0.931 | 0.925 | 0.914 | 0.908 |
| CHR5_i| 1,000 | 1,000 | 0.984 | 0.971 | 0.957 | 0.945 | 0.935 | 0.925 | 0.916 | 0.909 | 0.901 | 0.896 |
| CHR5_j| 1,000 | 1,000 | 0.978 | 0.964 | 0.943 | 0.926 | 0.916 | 0.907 | 0.897 | 0.894 | 0.889 | 0.885 |
| CHR5_k| 1,000 | 1,000 | 1,000 | 0.992 | 0.983 | 0.975 | 0.967 | 0.959 | 0.953 | 0.946 | 0.941 | 0.936 |
| CHR5_l| 1,000 | 1,000 | 0.990 | 0.981 | 0.961 | 0.947 | 0.937 | 0.928 | 0.921 | 0.916 | 0.911 | 0.907 |
| CHR5_m| 1,000 | 1,000 | 0.990 | 0.974 | 0.957 | 0.941 | 0.929 | 0.919 | 0.910 | 0.903 | 0.897 | 0.892 |
| CHR5_n| 1,000 | 1,000 | 0.997 | 0.990 | 0.975 | 0.964 | 0.954 | 0.946 | 0.939 | 0.934 | 0.929 | 0.925 |
| CHR5_o| 1,000 | 1,000 | 0.995 | 0.985 | 0.973 | 0.962 | 0.952 | 0.943 | 0.935 | 0.928 | 0.922 | 0.917 |

Fig. 42. Distribution of nodes numbers in the layers for all graphs

In the charts given below the comparison of the maximum number of nodes appearing in the layers of all analyzed graphs is presented.
On the basis of Fig. 42 and Fig. 43 it seems to be sufficient to analyze the distributions of numbers occurring in the first few layers to select a graph having the best basic parameters. This obviously reduces the time and effort for comparisons. The results again confirm that CHR5_k seems to be superior in terms of these basic parameters.

![Fig. 43. Distribution of the number of nodes in the first six layers](image)

| Graph  | $d=1$ | $d=3$ | $d=5$ | $d=6$ |
|--------|-------|-------|-------|-------|
| Number of nodes in layer | Number of nodes in layer | Number of nodes in layer | Number of nodes in layer |
| 0 | 10 | 50 | 100 |
| 1 | 20 | 60 | 150 |
| 2 | 30 | 90 | 200 |
| 3 | 40 | 120 | 250 |
| 4 | 50 | 150 | 300 |
| 5 | 60 | 180 | 350 |
| 6 | 70 | 210 | 400 |
| 7 | 80 | 240 | 450 |

In order to make an objective assessment of the CHR5_k parameters, they were compared to the parameters of the Reference Graph as previously described. Table 41 and Fig. 44 show the distribution of nodes in different layers of these two graphs, as a function of their diameters.
Fig. 44. Comparison of nodes number in successive layers

In Table 41 the total number of nodes in CHR5_k and reference graphs is compared for different diameters.

| D(G) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|------|----|----|----|----|----|----|----|----|----|----|
| CHR5_k | 5  | 20 | 80 | 284| 895| 2520| 6333| 14334| 29636| 56770|
| Reference Graph | 5  | 20 | 80 | 320| 1280| 5120| 20480| 81920| 327680| 1310720|

Table 41. Total number of nodes in Reference Graph and CHR5_k

Fig. 45. Comparison the number of nodes in layers and total number of nodes versus layer number

In Fig. 45 a comparison of node numbers in successive layers and total number of nodes as a function of number layer in ideal CHR5_k and Reference Graph is shown.

Table 42 and Fig. 46 show a comparison of the average length as a function of the both graphs diameter, taking into account the total number of nodes corresponding to this diameter. As in the previous comparisons $E_{nav}$ (54) is used.

| D(G) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|------|----|----|----|----|----|----|----|----|----|----|
| CHR5_k | 1.0000 | 1.0000 | 1.0000 | 0.9920 | 0.9829 | 0.9747 | 0.9669 | 0.9595 | 0.9527 | 0.9465 |
| $E_{nav}$ | | | | | | | | | | |

Table 42. The average path length as a function of the diameter
5. Conclusions

In this publication the analysis of a different construction of 5th degree chordal rings was presented. The authors’ main aim was to find structures which have the minimal diameter and minimal average of path in respect to number of nodes which create these graphs. Presented considerations in the paper have rather theoretical nature, without a strict reference to practical applications. It is difficult to imagine a real regular WAN communication network that consists of thousands of nodes. However the interconnection structures connecting thousands of microprocessors, or sensors require the construction of such networks as the regular ones. The main objective function for regular interconnection structures is to minimize the network diameter or average path length. So, this is the main reason why such the structures were analyzed and studied in our paper.

In this regard the program was worked out which allows to calculate the analyzed parameters. It allowed describing virtual reference graphs namely optimal and ideal graphs. In this way we also found chordal rings which possess the smallest difference regards to average path length and diameter, which Reference Graphs have. They examined many types of structures and concluded that parameters of the real graphs are slightly different of the theoretically calculated graph parameter values. The obtained results became the basis for preparing the general formulas for determining these parameters without the need of simulation. As a side-result of the paper, we have shown that these reference graphs can be used for obtaining fairly good estimation of distance parameters in a simple manner. Additionally, they concluded that it is enough to inspect the maximal number of nodes which can appear in first few layers in aim to choose the best topology.

This publication presents the results of analysis of the modified chordal rings fifth degree. This analysis was carried out for 15 graphs divided into 3 groups. Each of the group included 5 types of graphs. Since the graphs were analyzed are regular graphs odd degree, hence all the graphs have to have an even number of nodes. The nodes number of all graphs belonging to the first group is divisible by two, the second and the third by four (it follows from used method of their construction).
For each group of graphs their analysis based on results obtained thanks to the application of testing programs constructed by authors. It made possible to carry out a distribution of maximal number of nodes in layers, to count total number of nodes in virtual, optimal graphs. Based on obtained results, for the first two groups of graphs they found strict mathematical expressions describing the distribution of nodes in layers, the total number of nodes, the average path length for optimal graphs, whilst for the third group such formulas were not found. Additionally the prepared programs allowed us to compare the basic parameters of real and theoretically constructed graphs.

Among the all analyzed graphs, the structures CHR5_f – CHR5_o have the most acceptable basic parameters. Those graphs however have a fundamental limitation: the network should consist of nodes with nodes number has to be divisible by 4. The parameters of these networks in more or less deviate from the parameters of the reference graph (graph ideal), and what's involved, they are usually asymmetrical (depending on the choice of the source node, obtained values differ). Also, computational process is rather complex, and takes long time.

From the point of view of application, according to the authors, the most appropriate structure of the regular network topology are graphs CHR5_b. These chordal rings are symmetrical, their parameters, if are not equal to the parameters of optimal graphs, they are very close to them; they are simple and easy to design and implement. The main limitation is the fact that the number of nodes, creating these networks, has to be even, but this follows from the assumption that the structure has to be regular, and the degree of nodes is five. Fig. 47 shows the comparison of the best two structures.

As the justification of this last conclusion the presented above diagrams can be used. In Fig. 47 we show the comparison of basic parameters of chordal rings CHR5_b and the best graph - CHR5_k. It can be observed that in up to 84 nodes, theoretically calculated parameters of both types of rings are identical, and up to 224 nodes - not much different from each another. Thus, taking into account the advantages of CHR5_b structure described before, it should be used to construct regular networks possessing not a huge number of nodes or in a large network consisting of a few identical regular structures.

Future work can focus on both theoretical and practical aspects. For the theoretical aspects, it would be a big help to find more precise and reachable bounds. This would make it
possible to assess graph types, and to know how close to optimal they are. Moreover, a more thorough study of how precise distance estimates can be given using ideal and optimal graph would be interesting. Such a study could also cover other types of graphs. Another direction for further research would be to study new groups of graphs.

More practical aspects could deal with analyzing how well the good theoretical properties translate into good network properties. This could be done through simulation of different network configuration and traffic scenarios, and/or by studying how feasible the graphs are for assignment of physical, optical or logical links. In order to demonstrate that the topologies are useful in real-world settings, case studies would be a good place to start.

6. Acknowledgment

The authors would like to thank Associate Professor Jens Myrup Pedersen and Assistant Professor Tahir Riaz from Aalborg University, Department of Electronic Systems, and Professor Dr. Mohamed Othman from Universiti Putra Malaysia, Department of Communication Technology and Networks, for a fruitful collaboration with the work on analyzing chordal rings and other network topologies. Their inputs for this chapter have been particularly valuable.

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