Performance evaluation of a Wireless Computer Network,

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Abstract

This paper presents a predicted target architecture of an integrated manufacturing and management system for a manufacturer of household appliances, based on a metropolitan-type infranet and an industrial process control and monitoring wireless network. To evaluate performance, a method developed earlier for packet switching networks with end-to-end acknowledgement was applied. The network is modelled as a set of closed routes consisting of a user and a series of service stations (communication links, switches, host processes). The paper describes the investigations carried out for the case study. Some consideration is given to the performance evaluation accuracy, basing on the validation work results obtained from simulation and measurements on the Polish pilot wide area network.

1. Introduction

The Computer-Integrated Manufacturing and Management (CIMM) systems are severely needed by prospective users, especially big and medium manufacturing enterprises. Many people start to realise that development and implementation of such systems is necessary for the manufacturing enterprises to be duly monitored and run in some optimum way, in accordance with some objective operational criteria. In opinion of the executive staff of many manufacturing enterprises visited by the authors, such optimisation of complete enterprises is or will be soon a prerequisite for their existence on the highly competitive market.

In spite of that, big manufacturers and vendors of the Computer Integrated Management (CIM) systems, having at their disposal financial resources sufficient to develop and implement at least pilot CIMM systems, are no apt to enter the manufacturing domain. The basic reason for that seems to be the fact that the big CIM system manufacturers and vendors do not possess at their disposal the designers and implementers educated and experienced enough to cope with both manufacturing and management issues. Such persons are, however, available; paradoxically, many of them are available in poorly developed countries where the designers must have possess a wide scope of experience in order that they are successful; unfortunately, they are dispersed in various industrial and/or research organisations and they do not have at their disposal the financial resources needed to develop novel ICT systems of the CIMM type.

In such circumstances, a reasonable duty of research and development workers seems to be to carry out the initial work on the prospective project of CIMM systems, even if no financing is available for such work. This work may be considered as a volunteer work or a work for the society (as it is called in the case-study country of Poland) that have financed their earlier research and development work or as an investment in their own future: the designers involved early on the prospective CIMM project will have high chances to be included in the project execution team if and when the CIMM project is established.

This initial work should also include the definition of the system topology (here, the wireless solution seems to be the most appropriate one for the actual solution since the systems of the current state of art should be applied for the novel solutions) and designer-friendly investigation methods to ensure adequate performance for hardware and software solutions under design.

A team of IT experts and process technologists was established and worked out an approach to development of CIMM systems that seems to be feasible, rather fast and economic [1,2,3], creating the basis for this paper.

2. Exemplary CIMM architecture

The pilot CIMM system was designed several years ago for the ex-biggest Polish manufacturer of household appliances, Polar, Wroclaw (the Enterprise), employing several thousand people. The target organisational structure of the Enterprise would be that depicted in Fig. 1.

For the general Enterprise organisation presented in Fig. 1, the wireless hardware network architecture of the CIMM system, depicted in Fig. 2, has been proposed. Logically, the architecture is based on the wireless metropolitan network operating under the TCP/IP protocol suite [4] and on the process control and monitoring network of the LonWorks type [5].

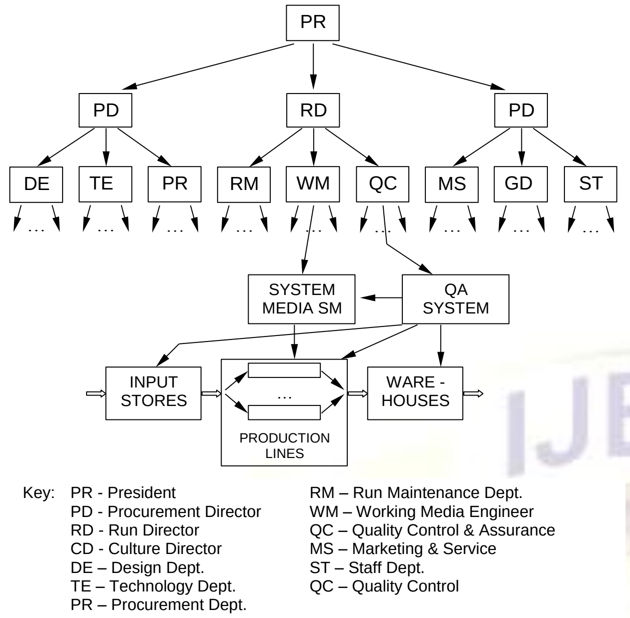


Fig. 1. General organisational diagram of the enterprise

3. The network under investigation

It is assumed that the time needed for transfer of data via any switch (server, gateway, node or router) is insignificant in comparison with the time needed to transfer the data via a co-operating data link. This is in conformity with the specifications of actual hardware proposed for the CIMM system since data is transferred via network switches as 8-bit byte blocks transferred via fast direct memory access (DMA) channels and internal processing of the data is usually connected only with the message headers.

However, the method proposed enables to consider the delays in wireless network switches though the calculations may be somewhat more complicated.

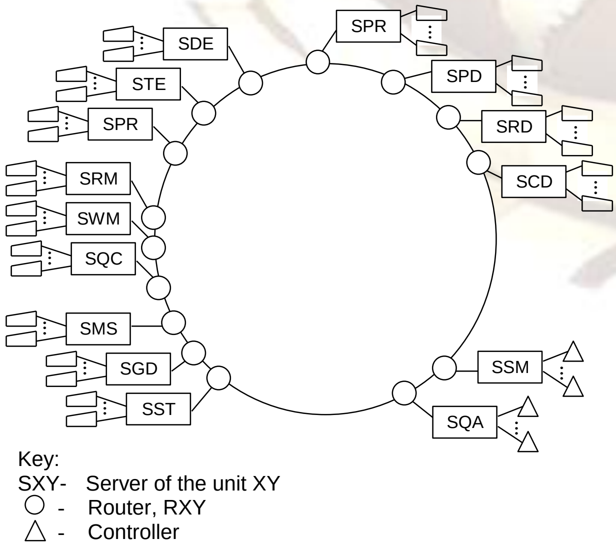


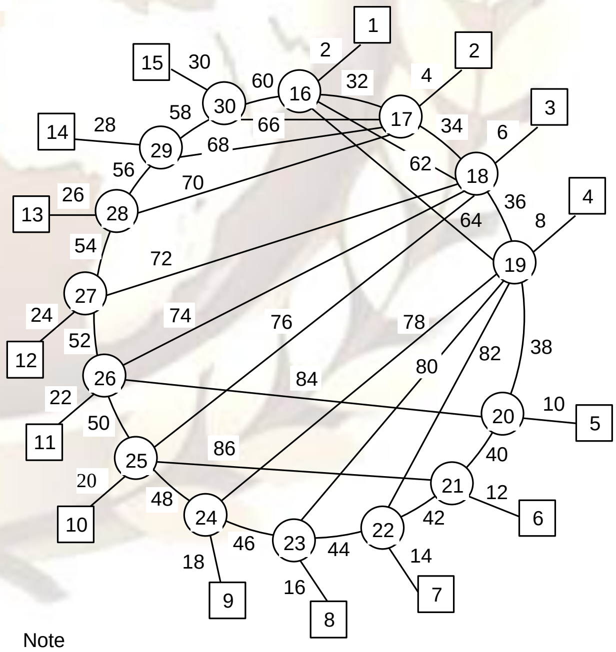
Fig. 2. Hardware architecture of the CIMM system

The hardware structure of the wireless CIMM system has been presented in Fig. 2. The case-study network depicted in Fig. 2 is composed of 30 switches (15 routers and 15 servers). Let the individual switches and data links be numbered as shown in Fig. 3 (server Nos: 1- 15, router Nos: 16-30, link pairs (for both transmission directions): (1,2) – (85,86).

Upon the wireless network of Fig. 3, there is stretched a set of closed routes, i.e. the calls from a user to its server and in the opposite direction. . Exemplary closed routes in the CIMM network are the connections between a Marketing & Service Department worker and the general enterprise database (the President's database) (closed route No. s = 166; ref. Fig. 4a) and between a technologist and the system Media database (closed route No. s = 279; ref. Fig. 4b).

Note: it is assumed that any p-th server, p ∊ 1,…,15 (ref. Fig. 3), is able to support 20 closed routes of numbers s = (p-1) 20, (p-1) 20 +1, …, (p-1) 20 + 19.

Note also that the network described here as a set of closed routes may be considered as a case of the Kelly networks [6] where the entity (packet) sojourn time in any switch is a function of the number of packets in all routes in the network. However, the classic queuing theory does not look for solutions for the Kelly networks [7,8].



Note
Link number, i =2k, k=1,2,..,43 is, in fact, a pair of numbers, 2k and 2k-1; the first is the number of the link directed from the node of the lower number to that of the higher one and the other in the opposite direction.

Fig. 3. Numbering of switches and links

Therefore, it was decided to adapt the approximate performance evaluation method [6], developed and validated earlier for telephone computer and communication networks with end-to-end acknowledgement, to the cases of the CIMM system implemented on wireless networks and to apply the method for performance evaluation for the case study under discussion.

4. The approximations

The reference [6] is hardly available now. Therefore, some basic assumptions and results will be repeated in the present paper.

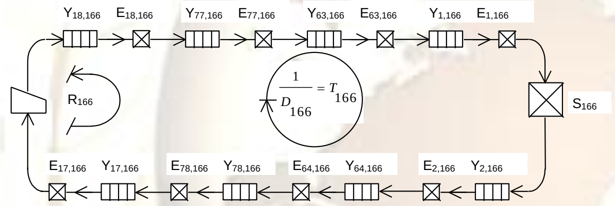
In addition to the denotations defined in Fig. 3, the following will be used in the present paper:

A_i is the set of closed routes beginning at the i-th link, such that the s(i)-th user is connected directly to the i-th link:

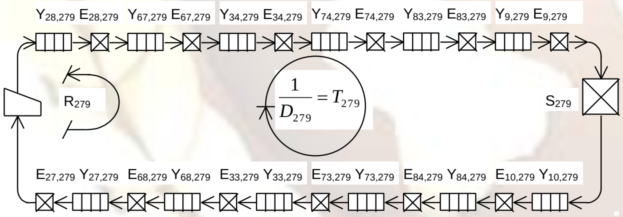
$$A_i = \{s_{i,1}, s_{i,2}, ..., s_{i,a_i}\} \quad (1)$$

B_i is the set of closed routes passing via the i-th link but not beginning at that link:

$$B_i = \{z_{i,1}, z_{i,2}, ..., z_{i,b_i}\} \quad (2)$$



a) Exemplary closed route of a Marketing & Service employee using general enterprise database



b) Exemplary closed route of a technologist using the System Media

Key:

- $s \in S=1,\dots,299$; $i \in I=1,\dots,86$
- R_s= round route (trip) delay for s-th closed route
- T_s= s-th closed route cycle time
- D_s= s-th closed route throughput
- $Y_{i,s}$= waiting time of s-th closed route to i-th link
- $E_{i,s}$= service time of s-th closed route to i-th link
- M_s= s-th closed route thinking time
- S_s= s-th closed loop ultimate service time

Note: Upper case letters denote random variables while lower case letters – relevant mean values

Fig. 4. Exemplary closed routes

The link preceding the i-th link in the s-th closed route is denoted by $h = h_s(i)$, provided that $s \in B_i$.

The set of closed routes parallel to the s-th closed route in the i-th link is defined by (3).

$$C_i = B_i \cap (A_h \cup B_h) \quad (3)$$

The power of C_i is given by (4).

$$\overline{C_i} = c_i \quad (4)$$

The mean cycle time of closed routes encountered by the s-th route at the i-th link is approximated by (5).

$$\bar{t}_{i,s} = \frac{a_i + b_i - 1}{\sum_{l \in \{A_i \cup B_i\}/\{s\}} \frac{1}{t_i}}; \frac{0}{0} = 0; \quad (5)$$

The mean waiting time of the closed routes encountered by the s-th route at the i-th link is given by (6).

$$\bar{y}_{i,s} = \frac{\bar{t}_{i,s}}{(a_i + b_i - 1)} \left(\sum_{l \in \{A_i \cup B_i\} \setminus \{s\}} \frac{y_{i,l}}{t_i} \right); \quad (6)$$

The mean service time for the closed routes encountered by the s-th route at the i-th link is given by (7).

$$\bar{e}_{i,s} = \frac{\bar{t}_{i,s}}{(a_i + b_i - 1)} \left(\sum_{l \in \{A_i \cup B_i\} \setminus \{s\}} \frac{e_{i,l}}{t_l} \right); \quad (7)$$

The mean thinking time for the closed routes encountered by the s-th route at the i-th link is given by (8).

$$\bar{m}_{i,s} = \frac{\bar{t}_{i,s}}{(a_i + b_i - 1)} \left(\sum_{l \in \{A_i \cup B_i\} \setminus \{s\}} \frac{m_{i,l}}{t_l} \right); \quad (8)$$

The definitions of the mean values defined above for the set of closed routes that are not parallel to the s-th route are as follows:

$$\bar{t}'_{i,s} = \frac{a_i + b_i - c_i}{\sum_{l \in \{A_i \cup B_i\} \setminus C_i} \frac{1}{t_i}}; \quad (9)$$

$$\bar{y}'_{i,s} = \frac{\bar{t}'_{i,s}}{a_i + b_i - c_i} \sum_{l \in \{A_i \cup B_i\} \setminus C_i} \frac{y_{i,l}}{t_i}; \quad (10)$$

$$\bar{e}'_{i,s} = \frac{\bar{t}'_{i,s}}{a_i + b_i - c_i} \sum_{l \in \{A_i \cup B_i\} \setminus C_i} \frac{e_{i,l}}{t_l}; \qquad (11)$$

$$\bar{m}'_{i,s} = \frac{\bar{t}'_{i,s}}{a_i + b_i - c_i} \sum_{l \in \{A_i \cup B_i\} \setminus C_i} \frac{m_{i,l}}{t_l}; \qquad (12)$$

For all closed routes, the balance equations (13) have been defined.

The set of equations (5) – (13) enables to compute iteratively the basic unknown mean values of the network performance, i.e. the closed route cycle time, t_s, the mean throughput in the s-th closed route, $d_s = \frac{1}{t_s}$, and the round-trip delay, $r_s = t_s - m_s$.

$$\bigcap_{s \in S} (t_s = \sum_{i \in I_s} (y_{i,s} + e_{i,s}));$$

where S is the set of all closed loops, $\bar{S} = v$;

$$\bigcap_{s \in A_i} (y_{i,s} = \frac{(a_i + b_i - 1)\bar{e}^2_{i,s}}{\bar{t}_{i,s}(1 - \frac{e_{i,s}}{t_s})} (\frac{1}{2} +$$

$$+ (a_i + b_i - 2)(1 - \frac{\bar{m}_{i,s}}{\bar{t}_{i,s} - \bar{e}_{i,s}}) \frac{\bar{y}_{i,s}}{\bar{t}_s - \bar{e}_{i,s}} +$$

$$+ (a_i + b_i - 1)(1 - \frac{\bar{m}_{i,s}}{\bar{t}_{i,s} - \bar{e}_{i,s}}) \frac{\frac{\bar{e}_{i,s}}{2}}{\bar{t}_{i,s} - \bar{e}_{i,s}}); (13)$$

$$\bigcap_{s \in B_i} (y_{i,s} = \frac{(a_i + b_i - c_i)\bar{e}'^2_{i,s}}{\bar{t}'_{i,s}(1 - \frac{e_{i,s}}{t_s})} (\frac{1}{2} + (a_i + b_i - c_i - 1)$$

$$(1 - \frac{\bar{m}'_{i,s}}{\bar{t}'_{i,s} - \bar{e}'_{i,s}}) \frac{\bar{y}'_{i,s}}{\bar{t}'_{i,s} - \bar{e}'_{i,s}} +$$

$$+ (a_i + b_i - c_i)(1 - \frac{\bar{m}'_{i,s}}{\bar{t}'_{i,s} - \bar{e}'_{i,s}}) \frac{\frac{\bar{e}'_{i,s}}{2}}{\bar{t}'_{i,s} - \bar{e}'_{i,s}}); \qquad (13)$$

5. Validation of the approximations

5.1. Validation with accurate results for cyclic queuing systems

The problem of performance evaluation of homogeneous star-topology networks is the same as that investigated for wireless queuing networks. The accurate solutions in the form of limit probabilities of the entity (packet, request) numbers have been known since early seventies. These results, for exponential thinking time, were employed to validate the approximations presented above.

Several hundred comparisons were done for the number of the customers (closed routes), v, changing between 2 and several dozen. The relative error of the mean cycle time, t_s, calculated for the set of comparison reached its maximum (less than 0.03) at $v \approx 14$ and decreased for v tending to zero or to infinity.

5.2. Validation with simulation

In order that the approximations may be validated, a fast Wide-Area-Network simulator was developed on the basis of earlier simulation studies for real-time computer control systems. This simulator was used, primarily, for the Polish pilot wide area network MSK. However, both actual and planned network configurations (including those to operate at much higher transmission rates) were investigated. In addition, available foreign simulation results for local and wide area networks were also used for validation.

The number of validation experiments was higher that 500, with the number of closed loops and links equal up to 500 and 100, respectively. The maximum relative error found was lower than 0.08. However, in the case of results obtained earlier, where the fair conditions of comparison could be ensured, the maximum relative error of the cycle time (and throughput) was lower than 3.5.

5.3. Validation with measurements

To investigate MSK and the approximations presented above, an internal communication network measuring tool Sitwa was developed and implemented. It was used, primarily, to validate the simulation results on the existing possible configurations of MSK. The investigations showed that the simplifying assumptions in simulation (e.g. omission of the flow control packets and/or frames) did not result in significant simulation errors. The maximum relative error of the approximations under discussion did not exceed 0.05.

6. Wireless CIMM investigation scenario

To produce some severe traffic conditions for the wireless CIMM system under investigation, it has been assumed that a major failure occurs in the Enterprise, of impact upon all departments. All users operate at one time trying to locate the problem within their responsibility ranges. Most of them (ca. nine per ten) use then the general Enterprise database (SPR), some try to analyse the current process conditions and to communicate with the System Media (SSM) or the Quality Control System (SQA). The basic routing arrays in the closed routes are set up so that the minimum possible number of lines is used in each closed route, provided that data transfer routes follow the hierarchy levels in the Enterprise. The use of the back-up routes may, possibly, produce even more severe traffic conditions. However, they are used only for very severe wireless CIMM system failures. In such cases, however, the main objective for the CIMM system operation is to recover the normal operating conditions as fast as possible and any optimisation of the transmission conditions is not of major interest then.

It is assumed that the data transfer rate in each link is equal to 1 Mbit/s. Each subscriber sends a short message of the mean length 100 bits (bit stuffing, i.e. insertions o a 0 bits after each five 1 bits in a sequence, included) that needs 10^{-4} s for transmission across any line along the route to the final server, and receives the 100,000 bit-long reply that needs 0.1 s for the transfer across any link on the route back to the subscriber.

The thinking time mean value, m_s, has been changed from 30 s down to ca. 0 s; this reflects the change-over from the interrogating transfer mode to the automatic file transfer mode (bulk transfer mode). It will be assumed that the service time at the final station of each closed loop is 0 s.

Let $I_s = \{i_{i,s}, i_{2,s}, ..., i_{k_s,s}\}$ be the set of links passed by the s-th closed route.

7. Exemplary results

The set of equations (5) ÷ (13) was solved iteratively. The basic user characteristics, r_s and d_s, for the exemplary closed routes, s = 166 and s = 279, are presented in Figs. 5 ÷ 8.

The exemplary round-trip delay (r_{166}) curve versus the mean thinking time (m_{166}) is shown in Fig. 5.

The d_{166} values (the mean throughput values depicted in Fig. 6) show a definite saturation (congestion) at m_s values below ca. 0.5 s. If the mean offered load for the 166-th closed route is defined by (14) below:

$$t_{166}^{off} = \sum_{i \in 166} (e_{i,s} + m_s) \qquad (14)$$

then the increased offered load results in the decreased mean throughput, d_{166}, for the given scenario and for $m_s < 0 .5$ s, s=1,…,300.

The closed route, s = 279 (Fig. 7), shows only the acceptable r_s values (below 1 s while the values not greater than 2 s are acceptable as not annoying ones) and the d_s value is decreasing monotonically with the offered load increasing ($m_s \rightarrow 0$, s = 1,…,300) (Fig. 8).

The reason is that the 279-th closed route does not pass via any link under heavy traffic. Therefore, even when the mean thinking time is decreased towards zero, no saturation (congestion) occurs in the links passed by the 279-th closed route.

The closed route, s = 166, passes via the most severely loaded links, i = 1 and i = 2. This results in that r_{166} reaches more than 4 s at m_s values close to 0 (ref. Fig. 5).

If it is assumed that an annoying value (i.e. the value that can not be accepted by the Enterprise employees) of r_s is that higher than 2 s, then the m_s values below some 0.5 s should be avoided.

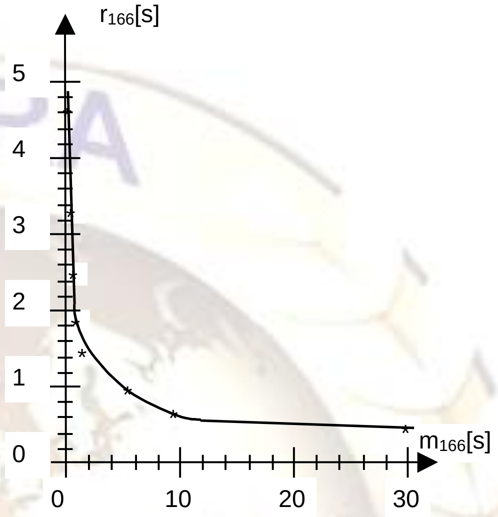


Fig. 5. r_{166} versus m_{166}

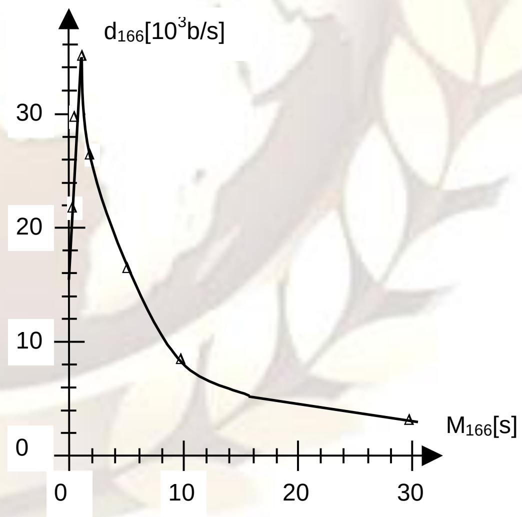


Fig. 6. d_{166} versus m_{166}

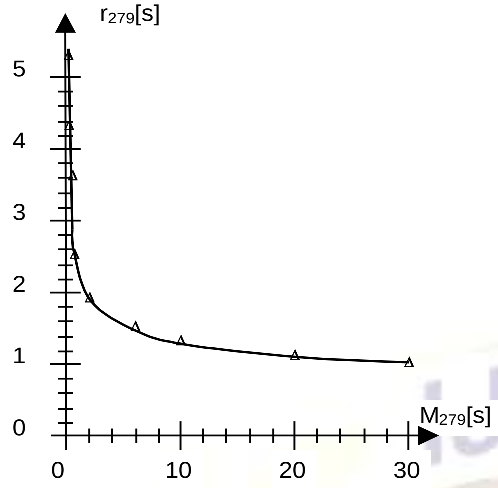


Fig. 7. r_{279} versus m_{279}

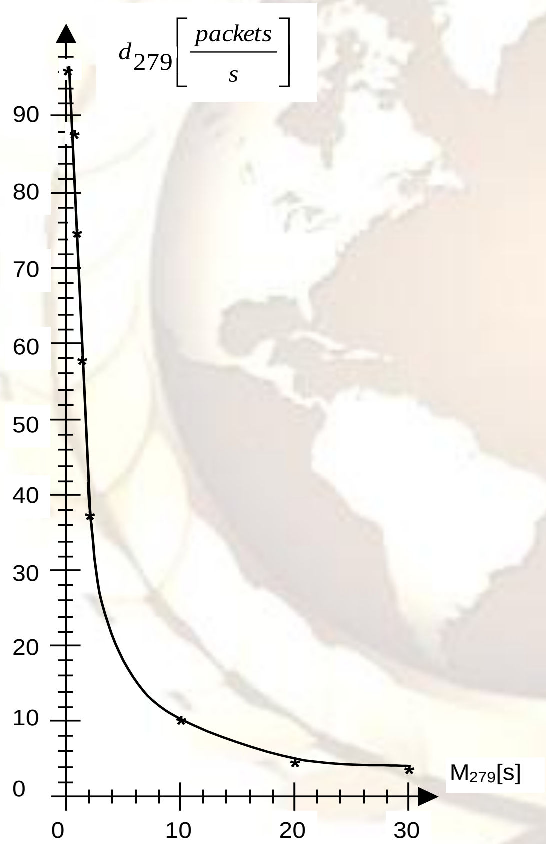


Fig. 8. d_{279} versus m_{279}

8. CONCLUSION

The authors do not claim that the method devised and verified some dozen years ago needs no further work. On the contrary, they do realise that the method validated primarily on the pilot Polish Interuniversity Computer Network MSK, operating at rather low transmission rates and in a limited configuration, needs further validation and possible tuning. In addition, the method may and should be upgraded: thanks to the rapid growth of the computing power that has happened during the last decade, more accurate approximations may be done for the balance equations (e.g., the simplifying assumption that an entity (packets) may find only one entity of one closed loop in the queue to some link) may be discarded. Then the balance equations become more complicated but may be still solved by the iterative method. And the networks with sliding windows or credit-based flow control may be modelled directly, instead of modelling several loops for credits bigger than 1, as it has been done earlier.

However, the authors believe that the method may and should be published in its original form now.. The authors are designers and/or consultants for actual computer systems and networks. To do their jobs in a proper way, they had to get involved in some research work in the domain of performance evaluation. And the results obtained can and, in the authors' opinion, should be applied in performance evaluation of various wireless networks (not only CIMMs) since the method is, at least, more simple that the well known performance evaluation methods such as Mean Value Analysis, and much more exactly tracks the network structure and, therefore, is much more useful for actual network designers.

8. References

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