Simulation of Wireless Network Throughput in Providing the Monitoring of Building Structures

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Abstract. The article shows the feasibility of using wireless networks in the field of construction monitoring. It is established that there is a need to increase the data transmission rate over the network in order to collect readings from distributed sensors in order to timely detect defects in building structures. An experiment with predefined parameters for the size of the transmitted packets was conducted using a software implementation of a model of network throughput assessment.

1. Introduction

More and more tasks in the modern world are being automated every day, and last but not least, the construction of buildings. Many aspects of construction have already been automated — you can see the semi-automatic marking of the terrain, electronic personnel accounting systems, digital construction models, and much more.

Technology development plays a key role in the construction of buildings, but at the same time, new technologies are changing consumer requirements for building operation. Nowadays, it is difficult to imagine a world without mobile communications, a workplace or office without Internet access, including wireless one — whether it is Wi-Fi, LTE, or fifth-generation mobile networks (5G).

The concept of complete safety of building structures involves monitoring the state of building structures. The use of wireless networks is the developing technology in the field of construction monitoring [1].

Wireless networks are a promising area to collect readings from distributed sensors in order to timely detect defects in building structures.

With the development of wireless technologies in the field of construction monitoring and an increase in the number of network users, there is a growing need to increase the speed of data transmission over the network. In this regard, it is necessary to search for feasible parameters at which the throughput of the data communication network will increase. Thus, the urgent task is to simulate the throughput of a Wi-Fi network in the distributed control mode.

Broadband wireless networks (BWN) under the control of the IEEE 802.11 protocol, best known as Wi-Fi, are the most widespread ones among wireless data transmission networks. [2,5]

The most famous papers that address the issues of developing mathematical models of wireless data networks include papers of Russian and foreign scientists such as: Vishnevsky V.M., Lyakhov A.I. [7], Baranov A.V., Kanatiev D.M., Zadorina D.A., Al shaev I.A., Lavrukhin V.A., Efimushkina T.V., Samuylov K.E., Bianchi G.[3,4], Cali F., Kim T.O., Choi B.D., Gupta. S., Chatzimisios P., Hadzi-Velkov Z., Natkaniec Marek, Karn P., Biba K., Wu H.[8], Yang X [9], Ye R. [10], Song N.[6], Deng J., Wang C., Chatzimisios P., Taifour M., Manaseer S.S., et al.
2. Wireless Networks with Distributed Control

Distributed control in 802.11 wireless networks involves transmission of data packets in two ways: using the Basic Access mechanism and using the RTS/CTS mechanism, or as it is also called an access method with a preliminary connection setup.

We will use the model [7] to simulate the information transmission.

Model constants defined by IEEE 802.11 are:

- SIFS, DIFS, and EIFS inter-frame gaps
- the length of a RTS frame and a CTS frame.

The model input parameters are:

- the number of stations in the network — $N$;
- the payload length of the transmitted data frames is the same and is equal to $L$ bytes;
- successful delivery confirmation frame length is $L_{ACK}$ bytes;
- $r$ is RTS/CTS threshold.

Network throughput $S$ is the output parameter, whose study and improvement is the aim of the simulation. Suppose that the probability of transmission start in an arbitrarily chosen virtual slot does not depend on the history list or on the current states of other stations and is the same for all stations in the network. The duration of the empty slot $T_e = \sigma$ is constant and strictly defined by the protocol.

Then

\[ p_e = (1 - \tau)^N \]  
\[ p_s = N(1 - \tau)^{N-1} \]  
\[ p_c = 1 - p_e - p_s \]

The durations of a successful slot and a collision slot are equal, consequently:

\[ T_s = \left(T_i^{DATA} + SIFS + T_i^{ACK} + DIFS\right) \]  
\[ T_c = \left(T_i^{DATA} + EIFS\right) \]

where $T_i^{DATA}$ and $T_i^{ACK}$ are the transmission times of the data frame and the delivery confirmation frame respectively, and SIFS, DIFS, and EIFS are the inter-frame gaps defined by the IEEE 802.11 protocol.

The length of one frame determines the average amount of information transmitted per successful slot, therefore: $U = L$.

The average network throughput $S$ for the basic access method is calculated by the formula:

\[ S = \frac{p_s U}{p_e \sigma + p_s T_s + p_c T_c}. \]

To calculate the probability of the transmission start to an arbitrarily selected virtual slot, we use the simple consideration that this probability is equal to the ratio of the average number of attempts to transmit a frame $f$ to the total number of virtual slots that have passed from the moment of frame transmission beginning until it was successfully completed or all transmission attempts were used. Thus, there is a formula:

\[ \tau = \frac{f}{\bar{\omega}} \]

where $\bar{\omega}$ is the average number of slots, in which the station is forced to delay the transmission of the current frame.

It is necessary to take into account that $p$ is the probability that at least one of the $n-1$ remaining stations transmits in a time slot in order to calculate the $p$ probability that a transmitted packet gets into a collision.

\[ p = 1 - (1 - \tau)^{n-1}. \]

A numerical solution of this expression, knowing the value of $p$, and, therefore, knowing the value of $\tau$, is found.

In the case of using the RTS/CTS mechanism to transmit packets, whose length is not equal, the formula (1) to calculate the network throughput will be slightly changed:
\[ S = \frac{p_s d}{T_{slot}}, \]  

where \( T_{slot} \) is the average duration of a virtual slot.

And the probability that the packet has a length \( l \) is equal to \( d_l \), therefore:

\[ d = \sum d_l \cdot l. \]

The distribution function will be calculated by the formula:

\[ D_l = \sum d_l \cdot l. \]

Since the RTS/CTS mechanism is used, the calculation of the duration of a successful and collision slot will depend on the RTS/CTS threshold. If the packet length exceeds it, then the RTS/CTS mechanism is used, otherwise the basic method is used.

Thus, the general formula to calculate the duration of a successful slot will look like:

\[ T_s = (1 - D_l)(RTS + CTS + 2 \cdot SIFS) + ACK + SIFS + DIFS + \sum d_l t_d(l), \]

where \( t_d(l) = \frac{H + B + l}{V} \) is time;

\( H \) is packet header;

\( l \) is the number of bytes;

\( V \) is the channel bit rate.

Collision slot duration will be calculated by the formula:

\[ T_c = \sum_{n=2}^{N} \pi_n \cdot t_c(n), \]

where \( \pi_n \) is the probability that the stations selected this slot for transmission, if it is known that a collision has occurred, \( t_c(n) \) is the average duration of a collision, provided that \( n \) stations got into a collision.

\[ \pi_n = \binom{N}{n} \left( \frac{1 - \tau}{\tau} \right)^{N-n} \cdot \frac{p_c}{n}, \quad n \geq 2, \]

\[ t_c(n) = (1 - D_p)^n RTS + \sum_{i=1}^{\beta} \left( (1 - D_p + D_l)^n - (1 - D_p + D_{l-1})^n \right) \cdot t_d(l) + EIFS. \]

After calculating the durations of successful \( T_s \) and collision slots \( T_c \) and substituting the obtained values in formula (2), we can find the throughput of the entire system as a whole.

### 3. Simulation of Wi-Fi Network Throughput in Distributed Control Mode

An R program was written in the RStudio integrated development environment, which allows you to read and display in the form of a matrix of values and in the form of a graph the network throughput with the specified parameters to simulate the Wi-Fi network throughput in distributed control mode.

Network throughput depends on the duration of the transmitted packet, since the size of the packet depends on how the transmission will occur: according to the Basic Method or using the RTS/CTS mechanism. A method to transmit a frame is selected by comparing the packet size with the threshold value of RTS/CTS. However, network throughput depends not only on the selected RTS/CTS threshold, but also on the size of the concurrent window. The channel usage efficiency depends on the duration of the CW concurrent window. The right choice of parameters for the delay mechanism greatly affects the throughput. Improper selection of CW parameters causes a decrease in throughput and the average packet delay can increase by several times.

Let’s apply the developed mathematical model to assess the network efficiency with various parameters for 50 stations with various parameters of the transmitted data. The number of stations was selected as the most optimal one due to the frequency of its use. In this case, we will vary the values of the CW delay window, the RTS/CTS threshold values, and the maximum value of the delay stage m.
We will also consider the values obtained for 15 and 100 stations for a detailed consideration of the obtained values.

The initial data transmission parameters were a 15-bit interval delay window size and an RTS/CTS threshold size of 200.

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**Table 1.** Throughput with a concurrent window value of 15, an RTS/CTS threshold value of 200, and with different values of the maximum delay stage

| N   | m  | thrput N | maxthrput | minthrput |
|-----|----|----------|-----------|-----------|
| 15  | 10 | 2.444788 | 3.299321  | 1.742885  |
|     | 25 | 2.485178 | 3.299321  | 1.742885  |
|     | 55 | 2.487101 | 3.299321  | 1.742885  |
| 100 | 10 | 1.877808 | 3.299321  | 1.742885  |
|     | 25 | 2.17395  | 3.299321  | 1.742885  |
|     | 55 | 2.246596 | 3.299321  | 1.742885  |

Figures 1 and 2 show that the value of network throughput for a larger number of stations depends more on the value of the maximum delay stage.

Figures 1 - Throughput with \( CW=15, \ m=10, \ 25, \ 55 \) and \( R=200 \) for operation of 15 stations

Figures 2 - Throughput with \( CW=15, \ m=10, \ 25, \ 55 \) and \( R=200 \) for operation of 100 stations

With a minimum value of the delay window, the highest throughput, when exchanging data between 100 stations, is observed when choosing the highest value of the delay stage.

These values were obtained when choosing a small threshold value \( (R = 200) \). Let’s consider a situation when the previously selected values of the delay window \( (CW = 15) \) and the best value of the maximum delay stage \( (m = 55) \) with various threshold values \( (R = 200, 400, 800) \) (Fig. 3 and Fig. 4) are taken.

Figures 3 - Throughput with \( CW=15, \ m=55, \ R=200, 400, 800 \) for operation of 15 stations

Figures 4 - Throughput with \( CW=15, \ m=55, \ R=200, 400, 800 \) for operation of 100 stations
The best value of throughput for operation of 100 stations is observed at the highest threshold value (R = 800). However, it is equal to only 2.617537 (Table 2).

**Table 2.** Throughput with different values of RTS/CTS, threshold value of 200, concurrent window value of 15, and with maximum delay stage of 55

| N   | R   | thrput N | maxthrput | minthrput |
|-----|-----|----------|-----------|-----------|
| 15  | 200 | 2.487101 | 3.299321  | 1.742885  |
|     | 400 | 2.741441 | 3.441673  | 1.775133  |
|     | 800 | 2.827160 | 3.488559  | 1.785456  |
| 100 | 200 | 2.246596 | 3.299321  | 1.742885  |
|     | 400 | 2.523778 | 3.441673  | 1.775133  |
|     | 800 | 2.617537 | 3.488559  | 1.785456  |

Let’s consider how the value of throughput will change with an increase in the delay window. To do this, let’s take different CW values with their maximum delay stages with the same RTS/CTS threshold value of 200 (Table 3).

**Table 3.** Throughput with different values of concurrent window and maximum delay stage, with RTS/CTS threshold value of 200

| N   | CW | m | thrput N | maxthrput | minthrput |
|-----|----|---|----------|-----------|-----------|
| 15  | 15 | 7 | 2.39495  | 3.299321  | 1.742885  |
|     | 31 | 6 | 2.692616 | 3.234244  | 1.665938  |
|     | 63 | 5 | 2.975962 | 3.180046  | 1.466327  |
|     | 127| 4 | 3.141416 | 3.155558  | 1.165278  |
|     | 255| 3 | 3.084022 | 3.084022  | 0.8219836 |
| 100 | 15 | 7 | 1.62846  | 3.299321  | 1.742885  |
|     | 31 | 6 | 1.835815 | 3.234244  | 1.665938  |
|     | 63 | 5 | 2.085398 | 3.180046  | 1.466327  |
|     | 127| 4 | 2.384273 | 3.155558  | 1.165278  |
|     | 255| 3 | 2.7129   | 3.143909  | 0.8219836 |

Figures 5 and 6 show that the maximum value of the throughput begins to shift towards an increase in the number of stations capable to transmit packets with a given throughput.

**Figures 5 -** Throughput with CW=15, 31, 63, 127, 255, m=7, 6, 5, 4, 3, R=200 for operation of 15 stations

**Figures 6 -** Throughput with CW=15, 31, 63, 127, 255, m=7, 6, 5, 4, 3, R=200 for operation of 100 stations

It was previously noted that throughput of 100 stations network is better with a threshold RTS/CTS of 800. Let’s consider how the network performance will change in this case (Table 4).
Table 4. Throughput with different values of concurrent window, maximum delay stage, with RTS/CTS threshold value of 800

| N  | CW  | m  | thrput N | maxthrput | minthrput |
|----|-----|----|----------|-----------|-----------|
| 15 | 7   | 2.745202 | 3.488559 | 1.785456 |
| 31 | 6   | 3.005737 | 3.410547 | 1.70411  |
| 63 | 5   | 3.238064 | 3.36619  | 1.495582 |
| 127| 4   | 3.345929 | 3.347032 | 1.183607 |
| 255| 3   | 3.233362 | 3.233362 | 0.8310448|

Figures 7 and 8 show that although the maximum throughput is observed with the smallest delay window, in this case the network throughput decreases uniformly with an increase in the number of stations. Therefore, the largest value of the delay window will be the best value for the operation of a large number of stations.

Let’s significantly increase the value of the delay window (CW = 255, 511, 1023) and consider the resulting network parameters (Table 5).

Table 5. Throughput for 15 stations with RTS/CTS threshold of 800

| N  | CW  | m  | thrput N | maxthrput | minthrput |
|----|-----|----|----------|-----------|-----------|
| 15 | 255 | 3  | 3.233362 | 3.233362  | 0.8310448|
| 511| 2   | 2.859187 | 2.859187 | 0.5200049|
| 1023|1    | 2.26416 | 2.26416  | 0.2972657|

Let’s consider what happens when the number of stations increases to 100 (Table 6).

Table 6. Throughput for 100 stations with RTS/CTS threshold of 800

| N  | CW  | m  | thrput N | maxthrput | minthrput |
|----|-----|----|----------|-----------|-----------|
| 100| 255 | 3  | 3.024891 | 3.337931  | 0.8310448|
| 511| 2   | 3.254445 | 3.3336   | 0.5200049|
| 1023|1    | 3.329741 | 3.329741 | 0.2972657|
Figure 9 shows that, for a small number of stations (N = 15), throughput is the highest when the smallest delay window (CW = 255) is chosen.

Figure 10 shows that the best value for the delay window for stations is CW = 1023. However, there are three intersections in the graphs, which show that each value of the delay window will be the best for a certain number of stations.

Let’s consider what parameters will be best to transmit data packets to 50 stations (Table 7). Despite the fact that the maximum value of throughput is observed when CW delay window of 255 is chosen, when transmitting packets between 50 stations, the network throughput will be greater with CW of 511.

Table 7. Throughput for 50 stations with an RTS/CTS threshold of 800

| N   | CW   | m   | thrput N | maxthrput | minthrput |
|-----|------|-----|----------|-----------|-----------|
| 50  | 255  | 3   | 3.267018 | 3.337931  | 0.8310448 |
|     | 511  | 2   | 3.329919 | 3.329919  | 0.5200049 |
|     | 1023 | 1   | 3.159087 | 3.159087  | 0.2972657 |

Figure 11 also shows that the best value for the delay window is CW = 511. With these parameters, the maximum network throughput is 3.329919.
Figure 12 shows a comparison of the initial parameters of the system with the final selected values, which shows how much the latter improve the network throughput indicator for 50 stations. Thus, the best parameters to transmit using 50 stations are the CW delay window of 511, the maximum delay stage $m$ of 2, and the RTS/CTS threshold of 800.

![Graph comparing initial and final parameters](image)

**Figures 12** – Comparison of the initial parameters of the system with the final selected values for operation of 50 stations

Thus, the network throughput with various values of the concurrent window, its maximum delay stage and RTS/CTS threshold value was found.

In this case, the value of throughput for 15, 50, and 100 stations was considered. The optimal number of stations was chosen, which is equal to 50.

Software implementation of the developed mathematical model was used to find the necessary parameters with which throughput of the 50 stations network is the greatest. The best parameters to transmit using 50 stations are the CW concurrent window of 511, with maximum delay stage $m$ of 2, and the RTS/CTS threshold of 800.

**4. Conclusion**

This article studies a model to assess the throughput of a wireless network in providing the high-speed data transmission, which takes into account influence of many factors. The distributed management mechanism in a wireless network running on the IEEE 802.11 protocol can be used in planning a wireless network to monitor the state of building structures in order to ensure the safety of buildings and structures. Data transmission in such a network occurs in two ways: using the Basic Access mechanism and the access method with a preliminary connection setup (RTS/CTS mechanism). An experiment with predefined parameters for the size of the transmitted packets and their distribution was conducted using a software implementation of a mathematical model of network throughput assessment. The network throughput directly depends on the duration of the transmitted packet, since the size of the packet depends on how the packet transmission will occur: according to the Basic Method or using the RTS/CTS mechanism. A method to transmit a frame is selected by comparing the packet length with the RTS/CTS threshold size. Network throughput depends not only on the selected RTS/CTS threshold, but also on the selected value of the concurrent window. The duration of the CW concurrent window affects the efficiency of the data transmission channel utilization. The network throughput depends on the correct choice of parameters of the delay mechanism. Improper selection of CW parameters causes a decrease in network throughput, and the average packet delay can increase by several times.
References

[1] Alazemi H.M.K.. Stochastic modeling and analysis of 802.11 DCF with heterogeneous non-saturated nodes. / Alazemi H.M.K., Margolis A., Choi J., Vijaykumar R., Roy S. // Computer Communications, 2007, vol. 30, no. 18, pp. 3652-3661.

[2] Alizadeh-Shabdiz F.. Finite Load Analytical Model for the IEEE 802.11 Distributed Coordination Function MAC. / Alizadeh-Shabdiz F., Subramaniam S. A. // IEEE International Conference on Communications, 2004, vol. 1, pp. 175-179.

[3] Bianchi G. IEEE 802.11 — Saturation throughput analysis // IEEE Commun. Lett. Dec 1998. Vol. 2. pp. 318—320.

[4] Bianchi G. Performance Analysis of the IEEE 802.11 Distributed Coordination Function // IEEE Journal on Selected Areas in Comm. — March 2000. — № 18 (3). — pp. 535—547.

[5] Duffy K. Modelling the 802.11 Distributed Coordination Function in Non-saturated Conditions. / Duffy K., Malone D., Leith D. // IEEE Commun. Letters, 2005, vol. 9, no. 8, pp. 715-717.

[6] Song N. “Enhancement of IEEE 802.11 distributed coordination function with exponential increase exponential decrease backoff algorithm” / Song N., Kwak B., Song J., and Miller L.E., // Proc. IEEE VTC 2003-Spring, vol.4, pp.2775–2778, 2003.

[7] Vishnevsky V.M., Lyakhov A.I. / IEEE 802.11 Wireless LAN: Saturation Throughput Analysis with Seizing Effect Consideration / Vishnevsky V. M. // Cluster Computing, April, 2002. Vol. 5. № 2. P. 133–144.

[8] Wu H. “IEEE 802.11 Distributed Coordination Function (DCF): Analysis and Enhancement” / Wu H. and Cheng S. // Proc. IEEE International Conference on Communications, vol. 1, pp. 605-609, Apr. 2002

[9] Yang. X “DSCR – A Wireless MAC Protocol Using Implicit pipelining” / Yang. X and Vaidya N.H.. // Technical report, Coordinated Science Laboratory, University of Illinois.2002.

[10] Ye R. “A Multichain Backoff Mechanism for IEEE 802.11 WLANs” / Ye R. and Tseng Y.-C. // IEEE Trans. on Vehicular Technology, vol. 55, Issue 5, pp. 1613 –1620, Sep. 2006.