Network Parameter Influence on Communications in Dense Wireless Nanonetworks

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ABSTRACT

This paper evaluates how various network parameters impact communication quality in a dense electromagnetic nanonetwork. The parameters studied are the symbol rate β (equal to the ratio of time between two consecutive pulses sent and the pulse length), communication range, node density, and pulse duration. The quality is measured by packet collisions, receptions, emissions, and deliveries to destination. The evaluation considers homogeneous and heterogeneous networks, and single and multiple packets per flow. Simulation results show how these parameters influence network communication quality; for example, increasing β reduces collisions and increases receptions, deliveries, and emission rates up to an optimal threshold, beyond which further increases in β have no significant effect. These insights provide guidelines for selecting appropriate network parameters.

CCS CONCEPTS

• **Networks** → **Network simulations**.

KEYWORDS

Electromagnetic nanonetwork, TS-OOK, β, pulse duration, communication range, node density

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1 INTRODUCTION

In recent years, there has been a noticeable increase in the development of electromagnetic nanonetworks, which are characterized by the use of small-scale devices for network communication. These networks are important due to their ability to enable information exchange (communication) within applications at the nanoscale, such as healthcare, environmental monitoring, multi-core processors, etc. [7]

In this paper, we consider dense nanonetworks, in which nodes have a high number of neighboring nodes. Some challenges of dense nanonetworks are to ensure reliable communication and to reduce the interference and collision rates due to the high node density. Addressing these challenges requires a comprehensive understanding of how various network parameters influence overall network communication quality.

Network communication quality can be measured by several metrics, such as the number of collided, received, delivered, and transmitted packets. Network protocols have a high influence on these metrics. In this paper, we demonstrate that even within the same protocol, outcomes can vary significantly due to different parameter values. The parameters we consider in this paper are β, node density, communication range, and pulse duration. In nanonetworks, β, i.e. the symbol rate, represents the ratio of time between two consecutive pulses and the pulse length, pulse duration represents the pulse length, communication range defines the effective distance over which communication occurs, and node density is the number of neighboring nodes per communication range.

The contributions of this paper are to reveal the impact of network parameters on packet collisions, receptions, emissions, and deliveries. This result can be used as a guideline for selecting appropriate network parameters in simulation studies.

The remainder of this paper is organized as follows. Section 2 presents the background on TS-OOK modulation, SLR protocol, and probabilistic flooding. Section 3 presents the related work. Section 4 presents how choosing network parameters such as β, communication range, density, and pulse duration influences network communication quality like collisions, emissions, reception, and delivery. Finally, the conclusion and future perspective are drawn in section 5.

2 BACKGROUND

2.1 TS-OOK

A nanonetwork consists of a set of interconnected nanomachines, devices that are a few micrometers at most in size. They are able to perform only very simple tasks such as computing, data storing, sensing, and actuation. They have applications in various fields, such as biomedical field, environmental research, military technology, and industrial and consumer goods applications.

In nanonetworks, the size constraints in nanodevices render the utilization of the ubiquitous carrier signals for transmission impractical. Instead, a very simple TS-OOK (Time Spread On-Off Keying) modulation has been proposed, based on femtosecond-long pulses in the terahertz band [5], appropriate for the very limited energy of nanonodes. Bits are sent through the emission of pulses interleaved by a constant duration, wherein a bit 1 is conveyed as

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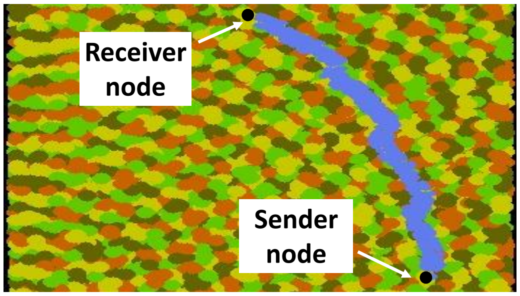

Figure 1: SLR routing phase, showing in blue the nodes sending packets, and numerous SLR zones.

a brief $T_p = 100$ femtosecond-long pulse, bearing energy, while a bit 0 is represented by a period of silence devoid of energy. Notably, both transmitters and receivers require high synchronization for effective operation.

Pulses are separated by intervals of T_s, and the symbol rate, β, is defined as T_s/T_p [5]. Choosing the optimal β value is challenging. When β equals 1, all symbols from a nanodevice are transmitted in a burst (through the hypothesis that the node hardware allows it), allowing only one nanodevice to access the channel at a given time. Conversely, as β increases, multiple nanodevices gain simultaneous access to the channel, even at the cost of reduced throughput for each individual device. The challenge lies in striking the right balance between β values to maximize network efficiency while accommodating multiple concurrent flows.

2.2 SLR Stateless Linear-path Routing

SLR [9] is a spatial addressing and routing protocol that comprises two phases: setup and routing.

The goal of the setup phase is to assign coordinates to nodes. These coordinates are defined as an integer number of hops from the node to each of some special nodes called anchors. During this phase, two anchors placed at the vertexes of 2D network broadcast a beacon containing one field representing the current number of hops (similar to a TTL, time to live, field). This field is initialized to zero and increments with each retransmission. At the end of this phase, the network space is divided in zones (the numerous small "squares" in Fig. 1) with unique coordinates that represent the distance in hops to each of the anchors. All nodes within the same zone have the same coordinates (zone coordinates) and that all the zones are disjoint (i.e. each node belongs to one zone only).

The goal of the routing phase is to route the data packets from source to destination in a linear routing path based on the coordinates assigned previously, as shown in Fig. 1. In this phase, packets contain the SLR coordinates of the source (sender) and destination (receiver), and each node receiving a packet checks whether it is on the path using a simple formula involving source and destination coordinates, and its own ones; if so, the node forwards the packet, elsewhere it discards it.

2.3 Probabilistic flooding

In probabilistic flooding, nodes forward packets with a predefined probability, discarding them if the probability threshold is not met. This is in contrast to pure flooding, which passes *all* messages to neighboring nodes. Using a sufficiently high probability, but much smaller than 1, probabilistic flooding maintains reliable message delivery while reducing the number of intermediate nodes involved in the relay process.

3 RELATED WORK

[4] discusses the influence of β and source packet rate on nanonetwork performance, concluding that higher β reduces the number of collisions. In contrast, our paper shows that β has an optimal value (beyond which collisions do not decrease anymore) and give examples on how to find it, and evaluates the effect of other parameters too (communication range, pulse duration, and node density).

[10] proposes a channel-aware forwarding scheme in nanonetworks, where data is forwarded either to all nodes (one-hop transmission) or only to neighboring nodes (multi-hop transmission). To achieve that, nodes use frequencies known to have small or big attenuation in the given transmission channel. They conclude that multi-hop forwarding yields higher capacity than single-hop transmission, while maintaining comparable delay. In contrast to this article, our paper discusses the effect of various parameters (including various communication ranges) to collisions, receptions, and emissions in multi-hop scenarios.

In underwater acoustic multi-hop, [1, 6] show that reducing the number of hops (through larger communication ranges) significantly reduces energy consumption per bit. Instead, our paper does not consider energy, but network metrics (collisions, receptions, etc.) using various parameters (communication range, density, etc.)

In our paper, we consider node density as a parameter. The density is also studied in [3], which describes the relationship between density and dissemination time, which denotes the duration for data to spread/share information throughout the entire network. It concludes that beyond a certain threshold of node density, the impact of node density does not significantly affect the data dissemination time, without compromising the achieved data quality. However, if the node density is smaller, then few people exchange data, leading to a slower data dissemination process.

Other papers also discuss various parameters and aspects that affect network behavior. For instance, [8] shows that end-to-end performance is influenced by route length, communication throughput depends on packet size and route length, route discovery time is affected by channel conditions and route length, and packet loss is not significantly affected by packet size or route length.

4 NETWORK PARAMETER INFLUENCE ON COMMUNICATIONS

In this section, we aim to explore and analyze the impact of various parameters on communications.

Our analysis needs ultra-dense nanonetworks with tens of thousands of nodes and several flows. Due to the impracticality of conducting real experiments in such a dense network and to the complexity , we need to resort to simulations. To the best of our knowledge, BitSimulator [2] is the only simulator capable of handling a high number of nodes. It has been used to validate results in various research papers[1]. Additionally, BitSimulator comes with a useful

[1]http://eugen.dedu.free.fr/bitsimulator

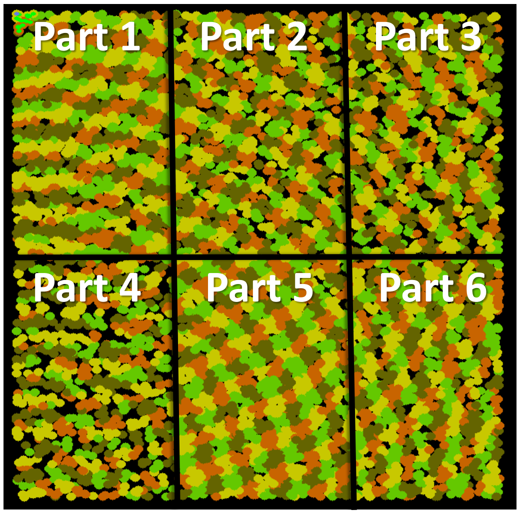

Figure 2: Heterogeneous network used in simulations.

Table 1: The parameters used in the evaluation (unless otherwise stated).

Parameter	Value
Size of simulated area	$6{,}000 \times 6{,}000$ µm^2
Number of nodes	10,000
Communication range for the SLR setup phase	220 µm
Communication range in routing	285 µm
β for the SLR setup phase	1,000
β in routing	100
Pulse duration	100 fs
Packet size	100 bit

visualization program (VisualTracer) that graphically displays the simulation events.

4.1 Base network scenario used for simulations

The simulations involve a 2D network with nodes randomly placed using a uniform distribution. The nodes remain static throughout the simulation.

We consider two node placements, a homogeneous one where all the nodes are placed in the whole network, and a heterogeneous one divided in six parts in a grid as shown in Fig. 2; for example, for 10,000 nodes, the six parts have 2,000, 1,500, 1,250, 1,000, 2,500 and 1,750 nodes, respectively.

Unless otherwise stated, the parameters used are shown in Table 1. We use the standard duration of pulse for TS-OOK modulation T_p = 100 fs (cf. [5]).

Simulations are executed on two numbers of packets, 1 and 20 packets per flow (chosen randomly). There are 9 distinct flows, illustrated in Fig. 3. They use SLR routing protocol, described in Sec. 2.2.

To ensure reproducibility of results and enhance trust in our study, all the results presented in this article are easily reproducible through a shell script, provided, along with all the related information, on Internet[2].

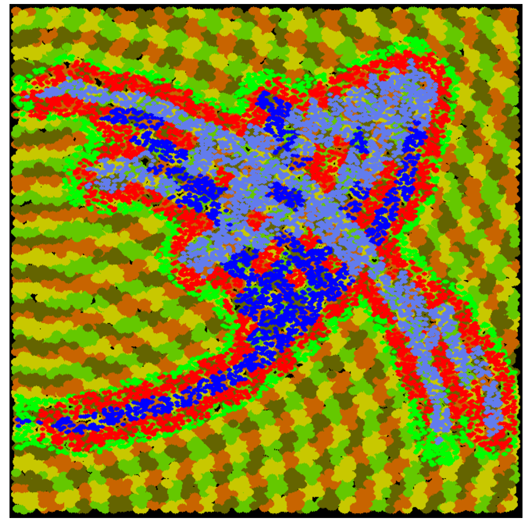

Figure 3: The network and the flows used in evaluation.

4.2 Impact of β

This section evaluates the impact of the parameter β (defined as T_s/T_p, where T_s is the time between two pulses, and T_p the pulse duration) on the communications, namely the number of packet collisions and packet deliveries at destination, and also on packet emissions and receptions at any nodes.

To allow fairer comparisons between different values of β, we vary β only during the routing phase, and keep it constant (equal to 1 000) during the SLR setup phase, so that the SLR zones are the same.

We evaluate a dozen values of β, chosen empirically. Table 2 presents only five representative values, allowing to discover the optimal β: a small value, three values close to the optimal β, and a big value.

The results in the homogeneous network are shown in Table 2. They show *two intervals*. In the first, called *improvement interval*, increasing β results in a reduction in packet collisions up to a certain point. In the second interval, called *stable interval*, increasing β does not influence packet collision. The value in between, called *optimal* β, marks the beginning of stabilization. In the following, we detail both intervals, and discuss the optimal value.

During the *improvement interval*, as the value of β increases, the occurrence of packet collisions decreases, resulting in a reduction in collision events. For example, when considering 1 packet per flow and 10,000 nodes (first column in the table), the number of packet collisions decreases from 79,096 to 8,307 when β increases from 50 to 600. Similarly, for 20 packets per flow and 30,000 nodes, the number of packet collisions decreases from 26,497,920 to 4,953,223 when β increases from 50 to 800. This correlation between β and collisions can be explained by the nature of β, defined as T_s/T_p, Increasing β essentially means increasing T_s, which, in practical terms, translates

[2] http://eugen.dedu.free.fr/bitsimulator/nanocom24

Table 2: Simulation results for various β values (and various number of nodes).

	1 packet per flow				20 packets per flow			
	Collisions	Receptions	Emissions	Deliveries	Collisions	Receptions	Emissions	Deliveries
Number of nodes = 10,000:								
β=50	79,096	120,532	2,763	96	1,604,771	2,409,555	55,589	1,734
β=600	8,307	195,912	2,828	157	224,523	3,865,111	56,627	3,022
β=800	8,307	195,912	2,828	157	224,515	3,865,119	56,627	3,022
β=1,000	8,307	195,912	2,828	157	224,515	3,865,119	56,627	3,022
β=50,000	8,307	195,912	2,828	157	224,515	3,865,119	56,627	3,022
Number of nodes = 20,000:								
β=50	513,624	342,677	5,976	103	10,251,368	6,529,716	117,131	1,916
β=600	62,614	812,850	6,106	270	1,491,852	16,057,697	122,342	5,385
β=800	62,559	812,905	6,106	270	1,683,221	15,875,253	122,399	5,345
β=1,000	62,559	812,905	6,106	270	1,683,221	15,875,253	122,399	5,345
β=50,000	62,559	812,905	6,106	270	1,683,221	15,875,253	122,399	5,345
Number of nodes = 30,000:								
β=50	1,419,223	527,299	9,099	121	26,497,920	10,480,326	173,083	2,158
β=600	315,845	1,704,604	9,445	467	5,009,060	35,160,560	187,820	10,317
β=800	315,738	1,704,711	9,445	467	4,953,301	35,422,690	188,761	10,243
β=1,000	315,738	1,704,711	9,445	467	4,953,223	35,422,768	188,761	10,243
β=50,000	315,738	1,704,711	9,445	467	4,953,223	35,422,768	188,761	10,243
Number of nodes = 40,000:								
β=50	2,525,690	725,299	11,346	117	49,626,133	14,521,433	224,045	2,140
β=600	570,410	2,668,848	11,280	536	10,395,777	59,168,229	242,766	10,631
β=800	562,700	2,676,558	11,280	541	10,845,635	59,006,143	243,780	10,610
β=1,000	562,700	2,676,558	11,280	541	10,843,521	59,008,257	243,780	10,622
β=50,000	562,700	2,676,558	11,280	541	10,843,521	59,008,257	243,780	10,622

to increasing the time spacing between two consecutive pulses, thereby allowing more flows to access the channel without collision. This relationship underscores the importance of optimizing β to minimize packet collisions.

As β increases and the number of collisions decreases, more packets are correctly received, hence the number of receptions increases. Indeed, in the table, for 20,000 nodes and 1 packet per flow, the number of received packets increases from 342,677 to 812,905 as β rises from 50 to 1,000; similarly, for 40,000 nodes and 20 packets per flow, the number of packets delivered (received at the destination zone) increases from 2,140 to 10,622 when β rises from 50 to 1,000.

More received packets generate more retransmitted packets. So, increasing β leads to an increase of emissions across all nodes, particularly visible in the dense network shown in the table.

During the *stable interval*, occurring when β is large, such as 1,000 and 50,000, the number of packet collisions remains the same, as exemplified for 30,000 nodes where it stabilizes at 315,738 in 1 packet per flow and 4,953,223 in 20 packets per flow. This stability is due to the probability of collision. For example, when sending or receiving 10 flows with $\beta = 800$, the probability of collision is very low, close to 0. Further increasing β to 1,000 does not change anything, i.e. the probability remains close to 0. Indeed, the probability of zero collision can be calculated as the product of the probabilities of each packet not colliding (1 minus probability of zero collision):

- probability of collision-free transmission for β=800: $\frac{799}{800} \times \frac{798}{800} \times \frac{797}{800} \times \frac{796}{800} \times \frac{795}{800} \times \frac{794}{800} \times \frac{793}{800} \times \frac{792}{800} \times \frac{791}{800} = 0.94$
- Probability of collision-free transmission for $\beta = 1,000$: $\frac{999}{1,000} \times \frac{998}{1,000} \times \frac{997}{1,000} \times \frac{996}{1,000} \times \frac{995}{1,000} \times \frac{994}{1,000} \times \frac{993}{1,000} \times \frac{992}{1,000} \times \frac{991}{1,000} = 0.95$

Thus, the probabilities of collision in scenarios with $\beta = 800$ and $\beta = 1,000$ are $1 - 0.94 = 0.06$ and $1 - 0.95 = 0.05$ respectively, which are nearly the same.

Given that the collision rate does not change, the number of received and emitted packets does not change either, as it can be seen in the table, for instance in one packet per flow and 10,000 nodes, when collision stabilizes at 8,307, the rate of packet reception and emission also remain stable at 195,912 and 2,828 respectively.

Concerning the *optimal value of* β, it varies according to the number of nodes and the number of packets transmitted (it increases when the number of nodes or number of packets sent increases). This variation is illustrated in Table 2: for scenarios with 1 packet per flow, the optimal β is 600 for 10,000 nodes, and 800 for 20,000, 30,000, and 40,000 nodes. Conversely, in scenarios with 20 packets per flow, the optimal β is 800 for 10,000 and 20,000 nodes, and 1,000 for 30,000 and 40,000 nodes.

To check the existence of the intervals and whether the optimal β is constant across other protocols, we conduct the same series of simulations in the probabilistic flooding (for 1 packet per flow). We do not present all the results (they can be found on the reproducibility Web page specified previously), but the important point is that the variation of beta yields an improvement and a stable interval, and an optimal β, like in SLR protocol. However, the optimal β differs with the routing protocol: it is 800 (in probabilistic protocol), compared to 600 (in SLR protocol) for 10,000 nodes; and 1,000 compared to 800 for 30,000 nodes.

To conclude, increasing β up to a point (called optimal β) reduces packet collisions and increases the number of packet receptions and transmissions; after this point, further maximizing β does not affect the number of collisions or reception and transmission. The optimal value of β increases with network density (number of nodes), and depends on the protocol, number of packets per flow, etc.

4.3 Impact of the communication range

In this section, we delve into the impact of communication range (the distance up to which a node receives the packet) on both the occurrence and mitigation of packet collisions, reception, and emission. We address a fundamental question: is it advantageous to use a larger communication range?

We present a series of simulations where we adjust the communication range while keeping the other parameters constant (given in Table 1). Note that, given that during the SLR setup phase the communication range impacts the size of zones during routing, for fairness and consistency across all simulations, we vary the communication range *only during the routing phase* and use the same communication range for the SLR setup phase, set to 220 µm (cf. Table 1). This ensures uniformity in the formation of zones in all our simulations. We also notice that the results for 1 packet and for 20 packets per flow are similar, hence, we present results only for 1 packet.

The results are presented in Table 3. They show that *increasing the communication range results in a higher number of collisions* in both homogeneous and heterogeneous networks. For instance, in the homogeneous network, a larger communication range results in an increase in collisions; for communication ranges of 285 and 500 µm, 39,960 and 269,332 packets collide, respectively. Similarly, in the heterogeneous network, the number of collisions rises from 37,966 to 243,107 as the communication range increases from 285 to 500 µm.

This phenomenon occurs because, as the communication range increases, more nodes communicate over a wider spatial area, enhancing their ability to interact with more neighboring nodes. As a result, having more nodes in reach increases the likelihood of overlapping transmissions and collisions within the network. Moreover, the extended communication range enables previously out-of-range nodes to potentially interfere with each other's transmissions, further increasing collision occurrences.

Table 3 also shows that a larger communication range increases the number of sent (emissions column in the table) and received packets (receptions and deliveries columns). A larger communication range implies more neighboring nodes to fall within reach, consequently, more packets are received, which in turn results in increased retransmissions (emissions) within the relay nodes.

In summary, the larger the communication range, the higher the collision rate and the number of both received and sent messages.

Finally, we note that it is up to the application to choose between both more collisions and more message deliveries (with a large communication range), and both fewer collisions and fewer message deliveries (with a small communication range).

4.4 Impact of the pulse duration

Pulse duration T_p refers to the length of time a signal remains in a high or low state, also known as its occupation time. This duration is typically determined by the characteristics of the modulation scheme and the hardware used for transmission and reception.

This section analyzes how pulse duration impacts the number of packet collisions, receptions, and emissions. In the simulations, we vary pulse duration while maintaining the same network scenario (given in Table 1) with 1 packet per flow.

The results are shown in Table 4. *An increase in pulse duration results in a decrease in the number of packet collisions*. For example, when the pulse duration increases from 10 to 800 fs, the number of packet collisions decreases from 63,172 to 24,859 for the homogeneous network, and from 72,126 to 19,046 for the heterogeneous network.

The increase in pulse duration correlates with a rise in the number of *packet receptions* (up to a point) at both the destination zone (deliveries in the table) and zones along the transmission path (receptions). For instance, in the homogeneous network, the number of packets received at intermediate zones increased from 139,994 to 173,690 as the pulse duration increased from 10 to 150 fs and then reduced to 100,743 as the pulse duration increased from 150 to 800 fs. Similarly, in the heterogeneous network, the number of packets received at the destination zone (deliveries) increased from 89 to 100 and then decreased to 91.

4.5 Impact of node density

This section presents how node density affects communications. In the simulations, we vary the number of nodes (hence the density) while maintaining the same network scenario and a homogeneous network. The node density can simply be computed as $\rho = n(\pi r^2/S)$, where n is the total number of nodes, $r = 285\,\mu m$ is the communication range, and $S = 6,000 * 6,000\,\mu m^2$ is the network surface (cf. Table 1). Thus, for 10,000, 20,000, 30,000, and 40,000 nodes in the network, the densities obtained are 70, 141, 212, and 283 neighbors per node, respectively.

Table 5 shows that increasing the density results in an increased collision rate and an increase in the number of packet receptions, emissions, and deliveries. Indeed, increasing density results in more neighboring nodes and more packets being transmitted, so more collisions and receptions occur.

5 CONCLUSION

This paper presents the influence of four network parameters (β, communication range, pulse duration and node density) on communications (packet collisions, emissions, receptions, and deliveries) in electromagnetic wireless nanonetworks.

Our findings are that increasing β (up to a point) reduces packet collisions while increasing the number of receptions, emissions, and deliveries; increasing β past this point has no significant effect. Increasing communication range or node density increases

Table 3: Simulation results for various communication ranges.

Comm. range [µm]	Homogeneous network				Heterogeneous network			
	Collisions	Receptions	Emissions	Deliveries	Collisions	Receptions	Emissions	Deliveries
285	39,960	162,733	2,807	117	37,966	183,821	2,951	111
350	72,730	249,519	2,969	162	73,226	267,375	3,011	127
450	178,075	360,315	3,016	172	169,028	392,268	3,004	161
500	269,332	390,008	3,000	180	243,107	451,081	3,020	157

Table 4: Simulation results for various pulse durations.

Pulse duration [fs]	Homogeneous network				Heterogeneous network			
	Collisions	Receptions	Emissions	Deliveries	Collisions	Receptions	Emissions	Deliveries
10	63,172	139,994	2,813	106	72,126	150,683	2,961	89
50	49,823	153,442	2,815	105	57,154	164,371	2,948	94
150	29,868	173,690	2,819	130	32,402	189,307	2,953	100
800	24,859	100,743	1,765	116	19,046	153,514	2,243	91

Table 5: Simulation results for various node densities.

Node density [nodes]	1 packet per flow				20 packets per flow			
	Collisions	Receptions	Emissions	Deliveries	Collisions	Receptions	Emissions	Deliveries
70	8,307	195,912	2,828	157	224,515	3,865,119	56,627	3,022
141	62,559	812,905	6,106	270	1,683,221	15,875,253	122,399	5,345
212	315,738	1,704,711	9,445	467	4,953,223	35,422,768	188,761	10,243
283	562,700	2,676,558	11,280	541	10,843,521	59,008,257	243,780	10,622

collisions, receptions, emissions, and deliveries. Increasing pulse duration reduces the number of packet collisions while increasing the number of packets received and emitted (up to a point).

These insights provide valuable information when choosing network parameters to enhance network usage.

Our future work intends to cover other network parameters and protocols.

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