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1 Introduction

Periodic and quick network-wide packet dissemination, *i.e.* flooding, is fundamental to many protocols used in today's Internet. Several flooding techniques exist [16, 24, 14] the simplest one relying on the principle that each node in the network forwards a flooded packet once – the first time it receives this packet. In wireless multi-hop ad hoc networks, flooding is an essential component of some of the most prominent routing protocols, such as OLSR [15], MANET extensions of OSPF [2, 5, 7] and AODV [13].

Due to the characteristics of the shared wireless medium [4], nodes in ad hoc networks must often forward flooded packets on the same interface they were received on. Upon reception of a flooded packet, nearby nodes are thus likely to simultaneously forward the packet on the shared wireless medium, and thus systematically cause packet collisions.

In order to reduce the number of such collisions in a distributed fashion, random back-off times are independently scheduled by each node before each transmission, which aims at avoiding synchronized wireless medium access. Such a mechanism, called *jitter* or *jittering*, was standardized by the IETF in RFC 5148 [10]. Jitter thus decreases the number of collisions at the price of increased delay.

During the time a node waits before transmitting, additional flooded packets may be received. According to RFC 5148, these packets are then buffered and piggybacked in the node's next transmission. This jittering technique also decreases the number of transmissions, at the price of longer transmissions, *i.e.* bigger packets.

Unintended jitter has been widely studied, both theoretically and based on experimental analysis, in the context of real-time services (such as for voice transport or video streaming) for several networking scenarios, in particular for ATM [20, 22] or IP wired and wireless networks [17, 12, 11].

Deliberate jitter was initially used in ALOHA and CSMA, which have been widely studied in the literature [23] [8]. The optimal jitter range has been studied experimentally in [18], while [3] proposed an analytical model for broadcast transmissions, taking a network-wide approach to describe the relationship between jitter range and probability of transmission without collision, and to evaluated the use of jitter at different layers.

This memorandum studies the use of jitter techniques specified by the IETF in RFC 5148 [10], in the context of flooding over multi hop wireless networks. An analytical model is introduced, and several results are derived concerning incurred delays, transmission rates reduction and packet size increase. These results offer a comprehensive view of the impact of jitter on flooding performance.

The remainder of this memorandum is organized as follows. Section 2 describes in detail the packet jittering technique. This section details the use of jittering techniques for preventing packet collisions in flooding. Section 3 presents an analytical model of the flooding operation in a link-state router. The impact of random delay in packet forwarding is studied in this analytical framework. Section 6 validates the results obtained in the previous section through simulations. Finally, section 7 concludes the memorandum .

2 The Jitter Mechanism for Flooding

This section details the use of jittering techniques, as specified in RFC 5148 [10], in the context of classical flooding, where each node in the network forwards a flooded packet once, the first time the packet is received. In this context, packet collisions occur when two neighboring nodes forward the same packet, immediately after its reception, as illustrated in Figure 1. It is worth to note that collisions in flooding addressed in this memorandum are systematic, *i.e.* they are come deterministically from the fact that two or more nearby routers take the same decision (to forward a flooded packet) in reaction to the same event (the reception of that packet). Prevention of these collisions, or at least reduction of them to random events with low probability, becomes thus a central issue to be handled for flooding in ad hoc networks.

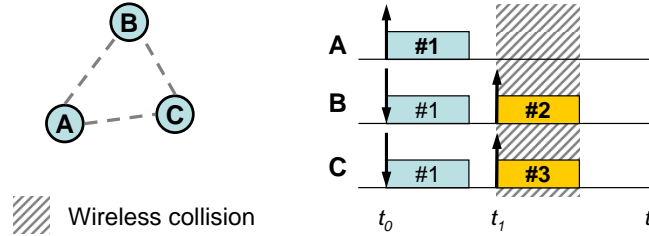


Figure 1: Wireless collision caused by concurrent flooding retransmissions. *The forwarding of a flooded packet (#1) by router A, received by B and C, causes simultaneous transmissions by routers B and C (#2 and #3), to forward the flooded packet, which cause a wireless collision.*

RFC 5148 [10] specifies techniques for reducing packet collisions occurrences. When an interface receives a message to be forwarded, a jitter value (denoted t throughout this memorandum) is selected randomly with a uniform distribution in the interval $[0, J_m]$, where J_m is the maximum jitter value (named by *MAXJITTER* in RFC 5148). According to the specification, such jitter values may be used for three cases of message transmission: periodic messages, externally triggered messages, and message forwarding. This memorandum focuses on the impact of jitter in flooded message forwarding. In the following, we will consider messages disseminated network-wide in flooded packets that may contain one or more messages. The motivation for using jittering techniques in this case is therefore two-fold (a) to reduce the number of wireless collisions by spreading message transmissions over time, and (b) to reduce the number of transmissions by piggybacking several messages in a single packet.

A wireless interface that receives a packet may decide to forward some of the messages contained in this packet. In this case, the interface assigns a jitter value to the messages to be forwarded – the same value for all messages belonging to the same packet – and schedules their transmission after the expiration of the time-out. A wireless interface may also itself generate messages to be flooded. Such self-generated messages are scheduled for immediate transmission, which is equivalent to assigning them a jitter equal to zero. Then, when a transmission is scheduled, all buffered messages waiting to be transmitted – that were either received from other interfaces in the mean time, or self-generated – are sent in

a single packet. The flowchart in Figure 2 summarizes this procedure, in which three elements can be pointed out:

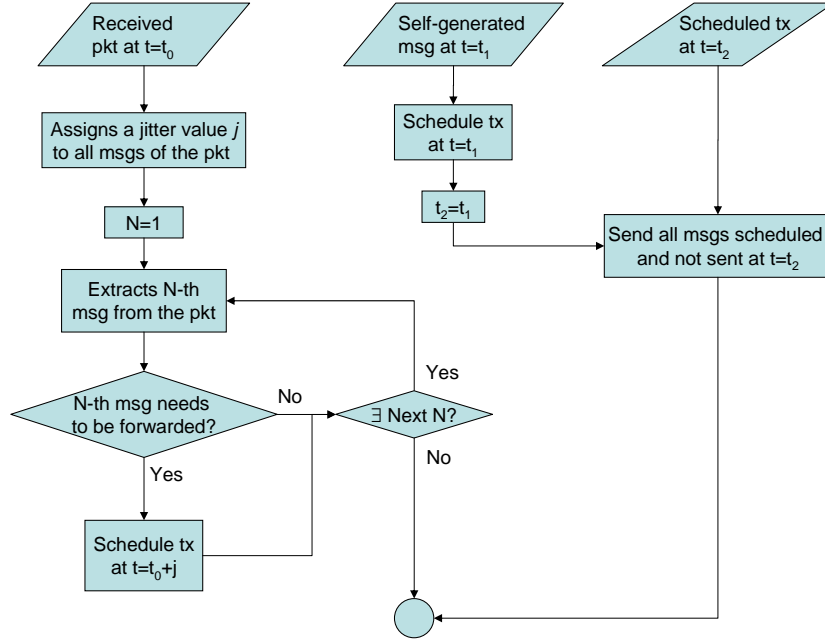


Figure 2: Forwarding algorithm with jitter.

- **Effective and scheduled time of transmission.** Messages are forwarded with a delay shorter or equal to their scheduled time, given the fact that *all* pending transmissions are performed together when the jitter of *any* pending message expires. The gap between scheduled delay and effective delay depends on the arrival rate of packets with messages to be forwarded.
- **Immediate flooding of self-generated messages.** The fact that self-generated topology description messages are sent immediately also contributes to the gap between scheduled and effective delays. Self-generated message rate, packet reception rate and jitter value bounds (*MAXJITTER*) are therefore factors that impact the effective delay of forwarded messages. If the self-generated message rate increases significantly, it may become the dominating factor and render irrelevant changes in the interval for jitter values.
- **Impact on packet rate.** Since forwarded packets may contain messages from one or more received packets, the use of jittering techniques leads to a reduction in the rate of flooded packets – even in cases where an interface forwards all the message it receives. In particular, a wireless interface sends packets at a lower rate than it receives packets to be forwarded. This is, however, at the expense of increasing the size of the forwarded packets, as they contain a growing number of messages.

	Packets	Messages
Received to fwd	λ_{in}	γ_{in}
Self-generated	λ_g	γ_g
Sent	λ_{out}	γ_{out}

Table 1: Traffic model variables.

The analysis presented in this memorandum evaluates the impact of the above three elements by way of a probabilistic theoretical model.

3 System Model

This section describes the main parameters and assumptions under which the jitter mechanism is evaluated. Section 3.1 defines the scope of this model and the variables used to parametrize operation of the jitter mechanism. Section 3.2 presents the types of traffic considered in the model and describes the assumptions over them.

3.1 Model Scope and Parameters

The model presented in this section examines the use of the jitter mechanism in a particular wireless router (denoted throughout this memorandum as a *node*) attached to a network, that participates in the flooding of traffic from other nodes and also generates traffic to be flooded over the network. It is assumed that all nodes in the network have the same configuration of the jitter mechanism. That implies that jitter values, denoted by t throughout this memorandum, are selected within the same interval $[0, J_m]$ and with the same distribution, where J_m is the maximum value for the jitter (denominated *MAXJITTER* in RFC 5148 [10]).

3.2 Traffic Model and Assumptions

Nodes participate in flooding by generating, receiving and forwarding *messages*. These messages are sent through the network in *packets*, each packet containing one or more messages.

Three types of traffic are distinguished:

- traffic received by the node to be forwarded (in-traffic),
- traffic generated by the node (self-traffic), and
- traffic sent by the node (out-traffic).

There may be an additional type of traffic: traffic received by the node, but not forwarded. For the purposes of this memorandum, this non-forwarded traffic is not relevant, and is thus not considered. For convenience, it will be therefore considered that all packets received are to be forwarded. Table 1 displays the variables used for describing the traffic rates in terms of messages per second (γ) and packets per second (λ), and Figure 3 illustrates the traffic model for a particular node.

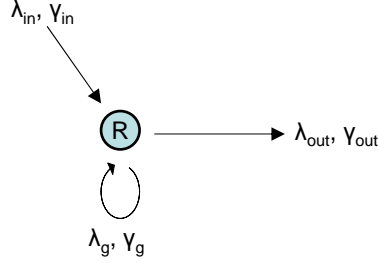


Figure 3: Node model.

Packet arrivals to the node (either self-generated or received from other nodes) are modeled as punctual homogeneous Poisson processes.

4 Analysis

This section presents the theoretical results of the analysis based on the previously presented jitter model. Results are presented for a general distribution of the random variable for jitter values, T_j , and then particularized for the case of uniform distribution, specified in RFC 5148, *i.e.*:

$$\begin{cases} f_{T_j}(t) &= \frac{\mathbf{1}_{[0, J_m]}(t)}{J_m} \\ F_{T_j}(t) &= \frac{t}{J_m} \mathbf{1}_{[0, J_m]}(t) + \mathbf{1}_{(J_m, +\infty)}(t) \end{cases} \quad (1)$$

Section 4.1 indicates the relationship between the different types of considered traffic, both in terms of messages and packets. The analysis focuses on the *collecting phase* of a node, which can be defined as follows:

- The **collecting phase** of a node using jitter for flooding over an ad hoc network is the period between the first in-packet arrival after an out-packet transmission, and the following out-packet transmission. Duration of this length is bounded by the jitter value assigned to such first in-packet.

Section 4.2 analyzes the average length of the collecting phase, denoted by $D(t)$, where t is the jitter value assigned to in-packet triggering the phase. Figure 4 illustrates the notion of collecting phase in a node reception/transmission timeline.

The average number of packets received during the collecting phase, as well as the impact of jitter in out-packet size, are studied in section 4.3. Based on these results, section 4.4 describes the out-packet rate, λ_{out} , in function of the in-packet and the self-packet rates, and checks its consistency by examining its asymptotic behavior when one of the two input traffic components (in-traffic and self-traffic) dominates the other. Finally, section 4.5 presents and describes the notion of cumulated delay of in-packets of a collecting phase, and computes the average delay for an in-packet, depending on the jitter interval.

4.1 Message and Packet Rates

This section describes the relationship between message and packet rates received and sent by a node. Every message that a node sends to the network

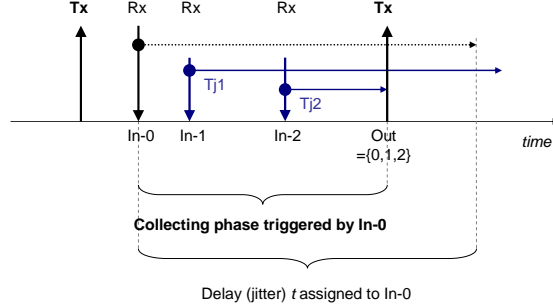


Figure 4: Collecting phase of a node participating in flooding.

(out-message) has been either received to be forwarded (in-message), or created by the node to describe its own topology (self-message). Therefore, message rates satisfy the following relationship:

$$\gamma_{out} = \gamma_{in} + \gamma_g \quad (2)$$

Packets contain one or more messages. For consistency, it is assumed that a self-generated packet contains one and only one self-generated message, that is:

$$\lambda_g = \gamma_g \quad (3)$$

The relationship among packet rates (λ_{out} , λ_{in} , λ_g) depends on the jitter mechanism. In-messages may be forwarded by way of (a) out-packets that contain only other in-messages, or (b) out-packets that contain one (and only one) self-generated message. The rate of out-packets in case (b) is then exactly λ_g . Out-packets in case (a) correspond to in-packets for which no self-traffic is generated while waiting for transmission. As out-packets in case (a) contain the messages from all the in-packets received, but not yet forwarded, the rate of out-packets in case (a) is significantly lower than the in-packet rate. If $M(t)$ denotes the average number of in- and self-packets whose messages are included in an out-packet, the out-packet rate can be expressed as follows:

$$\lambda_{out} = \frac{\lambda_{in} + \lambda_g}{\mathbb{E}_t\{M(t)\}} \quad (4)$$

Note that, as $M(t) \geq 1$, the out-packet rate is always smaller than the addition of in-packet and self-packet rates. Consequently, the average number of messages per out-packet (and thus the out-packet size) increases with respect to the number of messages per in-packet. This measure of the variation in packet size can be computed as follows:

$$\begin{aligned} \frac{\gamma_{out}/\lambda_{out}}{\gamma_{in}/\lambda_{in}} &= \frac{(\gamma_{in} + \gamma_g)/(\lambda_{in} + \lambda_g)\mathbb{E}_t\{M(t)\}}{\gamma_{in}/\lambda_{in}} = \\ &= \frac{(\gamma_{in} + \lambda_g)/(\lambda_{in} + \lambda_g)\mathbb{E}_t\{M(t)\}}{\gamma_{in}/\lambda_{in}} \end{aligned} \quad (5)$$

If self-packet rate is significantly lower than in-packet rate ($\lambda_g \ll \lambda_{in}$), then:

$$\frac{\gamma_{out}/\lambda_{out}}{\gamma_{in}/\lambda_{in}} \approx \mathbb{E}_t\{M(t)\} \quad (6)$$

Random variable $M(t)$ and its mean $\mathbb{E}_t\{M(t)\}$ are computed and examined in detail in section 4.3.

4.2 Average Duration of the Collecting Phase

This section studies the relationship between jitter values and length of collecting phases. Intuitively, the collecting phase is longer as the jitter value of the triggering in-packet increases, and gets shorter as the in-packet and self-packet rates (λ_{in} and λ_g , respectively) increase. *Theorem 1* describes rigurously the average duration of the collecting phase triggered by an in-packet arrival, denoted as $D(t)$, and its dependency on the jitter value t that such in-packet is assigned, the maximum jitter value, J_m and the traffic rates.

Theorem 1. *Let $D(t)$ be the average duration of the accumulating phase, with $t \in [0, J_m]$ being the scheduled time of retransmission of such first in-packet and J_m being the maximum jitter value. Then, $D(t)$ satisfies the following ODE:*

$$D''(t) = (-\lambda_{in}F_{T_j}(t) - \lambda_g)D'(t) \quad (7)$$

Proof. Given a scheduled jitter value t for the first in-packet, the effect of events happening in dt in the average duration D is examined. For sufficiently small values of dt , only one Poisson event (an in-packet arrival, with rate λ_{in} ; or a self-generated packet, with rate λ_g) may occur. An in-packet arrival at dt (with probability $\lambda_{in}dt$) may modify the duration $D(t)$ if the scheduled jitter T_j of the arrived packet is lower than the scheduled time of retransmission t ; a self-generated packet arrival within at dt (with probability λ_gdt) implies that the duration $D(t)$ becomes equivalent to the duration of the phase for a scheduled time dt . When no in- or self-packets arrive at dt , duration $D(t)$ is equivalent to the duration obtained by waiting a dt interval and then scheduling retransmission after an interval $t - dt$. This is described formally in the following transition equation:

$$\begin{aligned} D(t) = & \lambda_{in}dt \left(P(T_j > t)D(t) + \int_0^t f_{T_j}(x)D(x)dx \right) + \\ & + \lambda_gdtD(dt) + (1 - (\lambda_{in} + \lambda_g)dt)(D(t - dt) + dt) \end{aligned}$$

Then,

$$\begin{aligned} D(t) - D(t - dt) = & \lambda_{in}dt (P(T_j > t)D(t) + \\ & + \int_0^t f_{T_j}(x)D(x)dx) + \\ & + \lambda_gdtD(dt) - \\ & - (\lambda_{in} + \lambda_g)dt(D(t - dt) + dt) \end{aligned}$$

And dividing over dt ,

$$\begin{aligned} \frac{D(t) - D(t - dt)}{dt} &= \lambda_{in} (P(T_j > t)D(t) + \\ &\quad + \int_0^t f_{T_j}(x)D(x)dx) + \lambda_g D(dt) + \\ &\quad + (\lambda_{in} + \lambda_g)(D(t - dt) + dt) \end{aligned}$$

Dividing over dt and for $dt \rightarrow 0$, taking into account that $D(dt \rightarrow 0) \rightarrow 0$ by definition of D , the following differential equation arises:

$$\begin{aligned} D'(t) &= \lambda_{in} \left(P(T_j > t)D(t) + \int_0^t f_{T_j}(x)D(x)dx \right) - \\ &\quad - (\lambda_{in} + \lambda_g)D(t) + 1 = \\ &= \lambda_{in} \left((P(T_j > t) - 1)D(t) + \int_0^t f_{T_j}(x)D(x)dx \right) - \\ &\quad - \lambda_g D(t) + 1 = \\ &= \lambda_{in} \left(-F_{T_j}(t)D(t) + \int_0^t f_{T_j}(x)D(x)dx \right) - \\ &\quad - \lambda_g D(t) + 1 \end{aligned}$$

As $F_X(t) = \int_0^t f_X(x)dx$,

$$D'(t) = \lambda_{in} \int_0^t f_{T_j}(x)(D(x) - D(t))dx - \lambda_g D(t) + 1$$

Differentiating this expression over t :

$$D''(t) = \frac{d}{dt} \left[\lambda_{in} \int_0^t f_{T_j}(x)(D(x) - D(t))dx \right] - \lambda_g D'(t) \quad (8)$$

Where the derivative in brackets, denoted I_1 , can be calculated as follows:

$$\begin{aligned} I_1 &= \frac{d}{dt} \left[\lambda_{in} \int_0^t f_{T_j}(x)(D(x) - D(t))dx \right] = \\ &= \frac{d}{dt} \left[\lambda_{in} \left(\int_0^t f_{T_j}(x)D(x)dx - \right. \right. \\ &\quad \left. \left. - \int_0^t f_{T_j}(x)D(t)dx \right) \right] = \\ &= \lambda_{in} \frac{d}{dt} \left[\int_0^t f_{T_j}(x)D(x)dx \right] - \\ &\quad - \lambda_{in} \frac{d}{dt} \left[D(t) \int_0^t f_{T_j}(x)dx \right] = \\ &= \lambda_{in} f_{T_j}(t)D(t) - \lambda_{in} \frac{d}{dt} [D(t)F_{T_j}(t)] = \\ &= \lambda_{in} f_{T_j}(t)D(t) - \lambda_{in} D'(t)F_{T_j}(t) - \lambda_{in} D(t)f_{T_j}(t) = \\ &= -\lambda_{in} D'(t)F_{T_j}(t) \end{aligned}$$

Then, replacing I_1 in equation (8) leads to the ordinary differential equation (ODE) of order 2:

$$D''(t) = (-\lambda_{in} F_{T_j}(t) - \lambda_g) D'(t) \quad (9)$$

□

Corollary. *If jitter values are distributed uniformly within $[0, J_m]$, according to (1), the differential equation (7) has the following solution for $D(t)$:*

$$D(t) = \sqrt{\frac{2J_m}{\lambda_{in}}} e^{-\frac{\lambda_g^2}{2\lambda_{in}} J_m} \int_{\sqrt{\frac{J_m}{2\lambda_{in}}} \lambda_g}^{\sqrt{\frac{J_m}{2\lambda_{in}}} (\lambda_g + \frac{\lambda_{in} t}{J_m})} e^{-s^2} ds \quad (10)$$

Proof. The result is immediate by imposing initial conditions $D(0) = 0$, $D'(0) = 1$ and assuming an uniform distribution for jitter values within $[0, J_m]$.

□

4.3 Arrivals during the Collecting Phase and Packet Size

An out-packet sent at the completion of a collecting phase contains the messages included in the in-packet that triggered the phase, and the messages included in the in-packets arrived within the phase. In case that a self-packet is generated within the collecting phase, that terminates the phase and causes the transmission of the corresponding out-packet. *Theorem 2* proves that the average number of in- and self-packets included in an out-packet follows the Poisson law.

Theorem 2. *Let $M(t)$ be the average number of packets whose messages are transmitted together after the completion of a collecting phase started by an in-packet with initial jitter $t \in [0, J_m]$. Then, the expression of $M(t)$ is as follows:*

$$M(t) = 1 + (\lambda_{in} + \lambda_g) D(t) \quad (11)$$

Proof. When an in-packet, with initial jitter t , arrives to an interface and starts a collecting phase, the number of packets whose messages are sent together in the next transmission of such interface is:

$$M(t) = 1 + N(t)$$

Where $N(t)$ corresponds to the number of packets (in- and self-packets) arrived to the interface during the collecting phase – not including the in-packet that started such phase. For sufficiently small values of dt , the arrival of a self-generated message in dt implies that the out-packet is immediately sent, with only such self-message and the messages from the starting in-packet. In case that an in-packet arrives during dt , the number of packets included in the transmitted out-packet is incremented by one. The transition equation for $N(t)$ is therefore as follows:

$$\begin{aligned}
N(t+dt) &= \lambda_g dt + \lambda_{in} dt (P(T_j > t)(N(t) + 1) + \\
&\quad + \int_0^t f_{T_j}(x)(N(x) + 1)dx) + \\
&\quad + (1 - (\lambda_g + \lambda_{in})dt)N(t)
\end{aligned}$$

Which leads to the following ODE:

$$\begin{aligned}
N'(t) &= \lambda_g + \lambda_{in} (1 + (1 - F_{T_j}(t))N(t) + \\
&\quad + \int_0^t f_{T_j}N(x)dx) - (\lambda_g + \lambda_{in})N(t)
\end{aligned}$$

Differentiating over t :

$$\begin{aligned}
N''(t) &= \lambda_{in} (-f_{T_j}(t)N(t) + (1 - F_{T_j}(t))N'(t) + \\
&\quad f_{T_j}(t)N(t)) - (\lambda_g + \lambda_{in})N'(t) = \\
&= \lambda_{in}(1 - F_{T_j}(t))N'(t) - (\lambda_g + \lambda_{in})N'(t) = \\
&= -(\lambda_g + \lambda_{in}F_{T_j}(t))N'(t)
\end{aligned}$$

Which is the same ODE as (9). Assuming the following initial conditions:

$$\begin{cases} N(0) &= 0 \\ N'(0) &= \lambda_{in} + \lambda_g \end{cases}$$

The solution is therefore:

$$N(t) = (\lambda_{in} + \lambda_g)D(t)$$

□

Random variable $N(t) = (\lambda_{in} + \lambda_g)D(t)$, introduced in the proof of *Theorem 2*, computes the number of self- and in-packets arrived during the collecting phase (excluding the in-packet that triggers the phase). Similarly, the number of in-packets can be computed as:

$$N_i(t) = \lambda_{in}D(t) \tag{12}$$

Proposition 3 provides the expression of the mean of random variable $M(t)$ for uniform jitter, which comes immediately from the definition of mean and from (11).

Proposition 3. *In the conditions of Theorem 2, and with a uniformly distributed jitter within $[0, J_m]$, the mean of $M(t)$ w.r.t. the jitter value is as follows:*

$$\begin{aligned}
\mathbb{E}_t\{M(t)\} &= C_2 \left[C_1 (\lambda_{in} + \lambda_g)^2 \times \right. \\
&\quad \times \frac{2}{\sqrt{\pi}} \int_{\sqrt{\frac{J_m}{2\lambda_{in}}}\lambda_g}^{\sqrt{\frac{J_m}{2\lambda_{in}}}(\lambda_{in} + \lambda_g)} e^{-s^2} ds + 2\lambda_{in}^{\frac{3}{2}} + \\
&\quad \left. + 2\lambda_g \lambda_{in}^{\frac{1}{2}} \left(1 - e^{-\frac{J_m}{2}(\lambda_{in} + 2\lambda_g)} \right) \right] \tag{13}
\end{aligned}$$

Where C_1 and C_2 are defined as follows:

$$C_1 = \sqrt{2\pi J_m} e^{\frac{J_m}{2} \frac{(\lambda_{in} + \lambda_g)^2}{\lambda_{in}}} \quad (14)$$

$$C_2 = \frac{1}{2\lambda_{in}^{\frac{3}{2}}} e^{-\frac{J_m}{2}(\lambda_{in} + 2\lambda_g)} \quad (15)$$

Proof. From the definition of the mean:

$$\begin{aligned} \mathbb{E}_t\{M(t)\} &= \int_0^\infty M(t) f_{T_j}(t) dt = \\ &= \frac{1}{J_m} \int_0^{J_m} (1 + N(t)) dt \end{aligned}$$

Given that $f_{T_j}(t) = \frac{1}{J_m}$ for $t \in [0, J_m]$, and $f_{T_j}(t) = 0$ for $t > J_m$ or $t < 0$. The result is immediate by using (11) and applying standard algebra. \square

The result from *Proposition 3* allows to estimate the size increase of out-packets w.r.t. in-packets caused by jitter, as detailed in section 4.1 (eq. (6)), for the case that in-traffic dominates self-traffic ($\lambda_{in} \gg \lambda_g$). Figure 5 shows the evolution of $\mathbb{E}_t\{M(t)\}$ depending on λ_{in} , for different values of λ_g and $J_m = 1sec$.

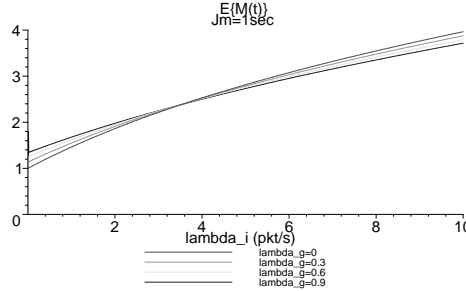


Figure 5: Mean of $M(t)$ (w.r.t. t) depending on λ_{in} , for different values of λ_g , $J_m = 1sec$.

Self-generated packets cause immediate transmission of out-packets. Therefore, increasing the self-packet rate reduces the duration of collecting phase in a greater extent than increasing the in-packet rate. It can be observed in Figure 5 that self-packet rate increase in λ_g causes a size growth of out-packets only for low values of λ_{in} ($\lambda_{in} \leq 4 \frac{pkt}{sec}$ in the figure). For moderate and high values of λ_{in} , increases in self-packet rate lead to smaller out-packets. This is due to the fact that arriving self-generated packets are likely to cause an out-packet transmission before the arrival of in-packets that would have been otherwise included in the transmitted out-packet.

4.4 Out-Packet Rate and Asymptotic Behavior

Proposition 3 completes the characterization of the out-packet rate, λ_{out} , defined in (16). The out-packet rate can be computed as follows:

$$\begin{aligned}
\lambda_{out} &= \frac{\lambda_{in} + \lambda_g}{\mathbb{E}_t\{M(t)\}} = \\
&= \frac{\lambda_{in} + \lambda_g}{1 + \mathbb{E}_t\{N(t)\}}
\end{aligned} \tag{16}$$

Figure 6 illustrates the evolution of the out-packet rate, λ_{out} , with respect to the in- and self-packet rates (λ_{in} and λ_g), for a constant value of $J_m = 1 \text{ sec}$. *Proposition 4* explores the asymptotic behavior of the out-packet rate in case of in-traffic and self-traffic dominance ($\lambda_{in} \rightarrow 0$ and $\lambda_g \rightarrow 0$, respectively), as well as its compatibility with the no-jitter behavior ($J_m \rightarrow 0$).

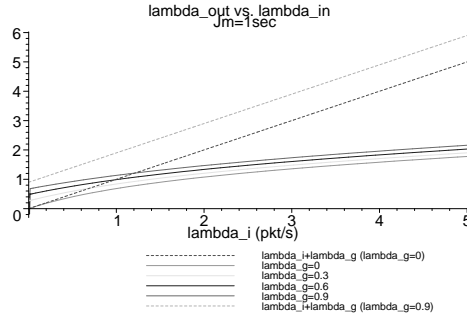


Figure 6: $\lambda_{out}(\lambda_{in}, \lambda_g)$, for $J_m = 0.5 \text{ sec}$.

Proposition 4. *The asymptotic behavior of the out-packet rate λ_{out} is as follows:*

$$\begin{aligned}
\lim_{\lambda_g \rightarrow 0} \lambda_{out} &= \frac{\lambda_{in}}{1 + \lambda_{in} \mathbb{E}_t\{D(t)\}_{\lambda_g=0}} \\
\lim_{\lambda_{in} \rightarrow 0} \lambda_{out} &= \lambda_g \\
\lim_{J_m \rightarrow 0} \lambda_{out} &= \lambda_{in} + \lambda_g
\end{aligned}$$

Proof. • $\lambda_g \rightarrow 0$:

$$\begin{aligned}
\lim_{\lambda_g \rightarrow 0} C_1 &= \sqrt{2\pi J_m} e^{\frac{J_m}{2} \lambda_{in}} \\
\lim_{\lambda_g \rightarrow 0} C_2 &= \frac{e^{-\frac{J_m}{2} \lambda_{in}}}{2\lambda_{in}^{\frac{3}{2}}} \\
\lim_{\lambda_g \rightarrow 0} \lambda_{out} &= \frac{\lambda_{in}}{C_2(C_1 \lambda_{in}^2 \frac{2}{\sqrt{\pi}} \int_0^{\sqrt{\frac{J_m}{2\lambda_{in}} \lambda_{in}}} e^{-s^2} ds + 2\lambda_{in}^{\frac{3}{2}})} = \\
&= \frac{\lambda_{in}}{\sqrt{\frac{\pi J_m \lambda_{in}}{2}} \text{Erf}\left(\sqrt{\frac{J_m}{2\lambda_{in}}} \lambda_{in}\right) + e^{-\frac{J_m \lambda_{in}}{2}}} = \\
&= \frac{\lambda_{in}}{1 + \lambda_{in} \mathbb{E}_t\{D(t)_{\lambda_g=0}\}}
\end{aligned}$$

- $J_m \longrightarrow 0$:

$$\begin{aligned}\lim_{J_m \rightarrow 0} C_1 &= 0 \\ \lim_{J_m \rightarrow 0} C_2 &= \frac{1}{2\lambda_{in}^{\frac{3}{2}}} \\ \lim_{J_m \rightarrow 0} \lambda_{out} &= \lambda_{in} + \lambda_g\end{aligned}$$

- $\lambda_{in} \longrightarrow 0$: Consider $M(t) = 1 + N(t)$, as defined in (11). Then, $\lim_{\lambda_{in} \rightarrow 0} M(t)$ can be computed as follows.

$$\begin{aligned}M(t) &= 1 + N(t) = \\ &= 1 + (\lambda_{in} + \lambda_g) \sqrt{\frac{\pi J_m}{2\lambda_{in}}} \frac{2}{\sqrt{\pi}} \times \\ &\quad \times \int_{\sqrt{\frac{J_m}{2\lambda_{in}}} \lambda_g}^{\sqrt{\frac{J_m}{2\lambda_{in}}} \left(\frac{\lambda_{in} t}{J_m} + \lambda_g \right)} e^{-s^2} ds \approx \\ &\approx 1 + (\lambda_{in} + \lambda_g) \sqrt{\frac{\pi J_m}{2\lambda_{in}}} \frac{2}{\sqrt{\pi}} \times \\ &\quad \left(e^{-\frac{J_m}{2\lambda_{in}} \left(\frac{\lambda_{in} t}{J_m} + \lambda_g \right)^2} - e^{-\frac{J_m}{2\lambda_{in}} \lambda_g^2} \right) \frac{\lambda_{in} t}{J_m} \\ &\approx 1 + t(\lambda_{in} + \lambda_g) \sqrt{\frac{\pi \lambda_{in}}{2J_m}} \frac{2}{\sqrt{\pi}} \times \\ &\quad \times \left(e^{-\frac{J_m}{2\lambda_{in}} \left(\frac{\lambda_{in} t}{J_m} + \lambda_g \right)^2} - e^{-\frac{J_m}{2\lambda_{in}} \lambda_g^2} \right)\end{aligned}$$

Therefore:

$$\lim_{\lambda_{in} \rightarrow 0} M(t) = 1 + 0 = 1$$

Which is a non-zero value that does not depend on t ; $\lim_{\lambda_{in} \rightarrow 0} \lambda_{out}$ can be therefore computed as the quotient of numerator and denominator limits, as follows:

$$\begin{aligned}\lim_{\lambda_{in} \rightarrow 0} \lambda_{out} &= \lim_{\lambda_{in} \rightarrow 0} \frac{\lambda_{in} + \lambda_g}{\mathbb{E}_t\{M(t)\}} = \\ &= \frac{\lambda_g}{1} = \lambda_g\end{aligned}$$

□

The results of *Proposition 4* are consistent with the intuitive behavior of jitter. When jitter is not used, the out-packet rate corresponds to the addition of in- and self-packet rates. When self-traffic dominates over in-traffic ($\lambda_g \gg \lambda_{in}$, that is, $\lambda_{in} \rightarrow 0$), the out-packet rate follows the self-packet rate, as self-generated packets cause immediate transmissions. In the inverse case, when self-traffic is negligible w.r.t. in-traffic ($\lambda_g \ll \lambda_{in}$, that is, $\lambda_g \rightarrow 0$), the jitter mechanism reduces the packet rate in a ratio that corresponds to the number of in-packets received during a collecting phase ($1 + \lambda_{in} \mathbb{E}_t\{D(t)\}$).

4.5 Average Forwarding Delay for In-Packets

This section addresses the average delay that an in-packet experiences, given a jitter configuration (defined by uniform distribution of assigned jitter values within $[0, J_m]$). Three steps are performed in order to characterize such delay. *Theorem 5* describes the cumulated delay of a collecting phase, $G(t)$, depending on the jitter value assigned to the triggering in-packet, t . The cumulated delay is the addition of the delays experienced by all in-packets (include the triggering in-packet) that arrive within the collecting phase. The result is then particularized for the case of uniform jitter. Based on this result, *Theorem 6* computes the average delay for in-packets; and this is particularized in the *Corollary* for uniform jitter.

Theorem 5. *Let $G(t)$ be the average cumulated delay in a collecting phase. Then, for an uniformly distributed jitter ($T_j \sim \text{Uniform}[0, J_m]$), the expression of $G(t)$ is as follows:*

$$G(t) = D(t) + F(t) \quad (17)$$

Where $D(t)$ is defined in (10) and $F(t)$ satisfies the following ODE:

$$F'(t) = \lambda_{in} D'(t) \int_0^t (1 - F_{T_j}(x)) dx \quad (18)$$

Proof. Let $F(t)$ be the cumulated delay not corresponding to the one from the in-packet that triggers the collecting phase, *i.e.* $F(t)$ is defined as $F(t) = G(t) - D(t)$. By restricting the time interval to a sufficiently small value of dt (as in proofs for *Theorems 1* and *2*), the arrival of a self-generated message implies that there is no additional delay. In case that an in-packet arrives, the additional delay corresponds to the total cumulated delay of such in-packet, $G(x)$ if the assigned jitter x for such packet is smaller than t , and $G(t)$ otherwise. The transition equation for $F(t)$ is therefore as follows:

$$\begin{aligned} F(t + dt) = & \lambda_{in} dt (P(T_j > t)G(t) + \\ & + \int_0^t P(T_j = x)G(x)dx) + \\ & + \lambda_g dt 0 + (1 - (\lambda_{in} + \lambda_g)dt)F(t) \end{aligned}$$

$$\begin{aligned} \frac{F(t + dt) - F(t)}{dt} = & \lambda_{in} (P(T_j > t)G(t) + \\ & + \int_0^t P(T_j = x)G(x)dx) - \\ & - (\lambda_{in} + \lambda_g)F(t) \end{aligned}$$

When $dt \rightarrow 0$:

$$\begin{aligned}
 F'(t) &= \lambda_{in} (P(T_j > t)G(t) + \\
 &\quad + \int_0^t P(T_j = x)G(x)dx) - \\
 &\quad - (\lambda_{in} + \lambda_g)F(t) = \\
 F'(t) &= \lambda_{in} (P(T_j > t)(G(t) - F(t)) + \\
 &\quad + \int_0^t P(T_j = x)(G(x) - F(t))dx) - \\
 &\quad - \lambda_g F(t)
 \end{aligned}$$

By definition, $G(t) - F(t) = D(t)$, therefore:

$$\begin{aligned}
 F'(t) &= \lambda_{in} (P(T_j > t)D(t) + \\
 &\quad + \int_0^t P(T_j = x)(G(x) - F(t))dx) - \\
 &\quad - \lambda_g F(t)
 \end{aligned}$$

Recalling that $G(t) - F(t) = D(t)$, and derivating again over t :

$$\begin{aligned}
 F''(t) &= \lambda_{in} (-f_{T_j}(t)D(t) + (1 - F_{T_j}(t))D'(t) + f_{T_j}(t)G(t) - \\
 &\quad - F'(t)F_{T_j}(t) - F(t)f_{T_j}(t)) - \lambda_g F'(t) = \\
 &= \lambda_{in}(1 - F_{T_j}(t))D'(t) - \lambda_{in}F_{T_j}(t)F'(t) - \lambda_g F'(t) = \\
 &= \lambda_{in}(1 - F_{T_j}(t))D'(t) - (\lambda_{in}F_{T_j}(t) + \lambda_g)F'(t)
 \end{aligned}$$

Multiplying by $D'(t)$ on both sides:

$$\begin{aligned}
 F''(t)D'(t) &= \lambda_{in}(1 - F_{T_j}(t))(D'(t))^2 - \\
 &\quad - (\lambda_{in}F_{T_j}(t) + \lambda_g)F'(t)D'(t)
 \end{aligned}$$

From (9), $D''(t) = -(\lambda_{in}F_{T_j}(t) + \lambda_g)D'(t)$ and therefore:

$$F''(t)D'(t) = \lambda_{in}(1 - F_{T_j}(t))(D'(t))^2 + D''(t)F'(t)$$

$$\begin{aligned}
 \frac{F''(t)D'(t) - D''(t)F'(t)}{D'(t)^2} &= \lambda_{in}(1 - F_{T_j}(t)) \\
 \left(\frac{F'(t)}{D'(t)} \right)' &= \lambda_{in}(1 - F_{T_j}(t))
 \end{aligned}$$

Applying the initial condition $F'(0) = 0$:

$$F'(t) = \lambda_{in} D'(t) \int_0^t (1 - F_{T_j}(x)) dx$$

□

Corollary. *If jitter values are distributed uniformly within $[0, J_m]$, according to (1), the differential equation (18) has the following solution for $F(t)$:*

$$\begin{aligned}
F(t) = & e^{\frac{J_m}{2} \frac{\lambda_g^2}{\lambda_{in}}} \frac{J_m^{\frac{3}{2}}}{\sqrt{\lambda_{in}}} \sqrt{\frac{2}{\pi}} \int_{\sqrt{\frac{J_m}{2\lambda_{in}}} \lambda_g}^{\sqrt{\frac{J_m}{2\lambda_{in}}} \lambda_g + \sqrt{\frac{\lambda_{in}}{2J_m}} t} e^{-s^2} ds \times \\
& \times \left(\lambda_g - \sqrt{\pi} \left(2 + \frac{\lambda_g^2}{\lambda_{in}} \right) \right) + \frac{t}{2} e^{-\frac{\lambda_{in} t^2}{2J_m} - \lambda_g t} - \\
& - \frac{J_m}{2} \left(1 - e^{-\frac{\lambda_{in} t^2}{2J_m} - \lambda_g t} \right) \left(\frac{\lambda_g}{\lambda_{in}} + 2 \right)
\end{aligned} \tag{19}$$

Proof. Applying the CDF of T_j in (18) leads to:

$$F'(t) = \lambda_{in} D'(t) \int_0^t \left(1 - \frac{x}{J_m} \right) dx = \lambda_{in} t \left(1 - \frac{t}{2J_m} \right) D'(t)$$

The result then comes from solving this equation with I.C. $F(0) = 0$. \square

The average forwarding delay for an in-packet can be computed by using results obtained in previous sections. *Theorem 6* describes the average forwarding delay for in-packets received within a collecting phase with jitter value t .

Theorem 6. *The average delay between reception and retransmission for a message contained in an in-packet has the expression that follows:*

$$T_{tx} = \int_0^{J_m} f_{T_j}(t) \frac{D(t) + F(t)}{1 + \lambda_{in} D(t)} dt \tag{20}$$

Proof. Within a collecting phase with jitter value t , the average cumulated delay of in-packets is $G(t)$. From (12), the average number of received in-packets is $N_i(t) = \lambda_{in} D(t)$. Therefore:

$$T_{tx}(t) = \frac{G(t)}{1 + N_i(t)} = \frac{D(t) + F(t)}{1 + \lambda_{in} D(t)}$$

Averaging over all possible jitter values for the collecting phase:

$$T_{tx} = \mathbb{E}_t\{T_{tx}(t)\} = \int_0^{J_m} f_{T_j}(t) \frac{D(t) + F(t)}{1 + \lambda_{in} D(t)} dt$$

\square

Corollary. *If jitter values are distributed uniformly, the average delay between reception and retransmission for a message contained in an in-packet is as follows:*

$$T_{tx} = \frac{1}{J_m} \int_0^{J_m} \frac{D(t) + F(t)}{1 + \lambda_{in} D(t)} dt \tag{21}$$

5 Discussion

The above section analyzes the benefit of using of jitter in terms of packet transmission rate reduction. This has been modeled by studying the out-packet rate λ_{out} and its relationship with variables λ_{in} (in-packet rate) and λ_g (self-generated packet rate), for a uniformly distributed jitter selected within $[0, J_m]$. The expression of $\lambda_{out} \equiv \lambda_{out}(\lambda_{in}, \lambda_g)|_{J_m}$ is detailed in equation (16). For the parameters chosen for representation in Figures 5 and 6 ($\lambda_{in} = 4pkt/sec$, $J_m = 1sec$) and $\lambda_g = 0.2pkt/sec$, for instance, the out-packet rate is $\lambda_{out} = 1.66pkt/sec$, which implies a packet rate reduction (w.r.t. in-packet rate) of 60%. For a more realistic value of $J_m = 100msec$, the out-packet rate becomes $\lambda_{out} = 3.49pkt/sec$, still a significant reduction in the number of transmissions. Less transmissions are indeed very desirable in wireless ad hoc networks, where bandwidth scarcity and hard energy constraints are common.

However, this benefit comes at the cost of additional delay. This delay is accumulated while packets are buffered and waiting for the next backed-off transmission that is scheduled. When an in-packet is received by an interface using jitter, messages contained in the packet are forwarded after a random delay. If such in-packet triggers a new collecting phase, then the time lapse before forwarding corresponds to the length of the collecting phase, for which the average in function of the jitter value t , $D(t)$, is described in equation (10). The length of the collecting phase is the upper bound or worst case for the random delay that an in-packet may experience. The average delay for in-packets, given a maximum jitter value J_m , is explored in equation (20). Even with a large jitter interval, as in the previous example ($\lambda_{in} = 4pkt/sec$, $\lambda_g = 0.2pkt/sec$, $J_m = 1sec$), and from eq. (21), such average delay is $T_{tx} = 0.24sec$; for the maximum jitter value $J_m = 0.1sec$, $T_{tx} = 0.04sec$. These delays can be thus scaled into acceptable values with the jitter range. Based on the results presented in section 4, Figure 7 displays the plot of the average of the collecting phase length, $D(T)$, and the average delay for an in-packet, $\mathbb{E}_t\{T_{tx}(t)\}$ for an interface with in-packet traffic rate $\lambda_{in} = 4 \frac{pkts}{sec}$ and self-packet traffic rate $\lambda_g = 0.2 \frac{pkts}{sec}$, where T is the average jitter value, distributed uniformly within $[0, J_m]$ with $J_m = 2T$.

Moreover, the benefit of reduced out-packet transmission rate comes also at the cost of longer transmissions (out-packets), as shown in eqs. (5), (6) and (11). In practice, IETF standardization activity indicates that jitter is used at the network layer, generally above a link layer using CSMA based mechanisms (typically 802.11). The effect of longer packets with CSMA has been studied in various prior work including in [21], where it is shown that if L is the length of packets and B the bit error rate, the achieved throughput G is:

$$\frac{L}{L+1}(1-B)^{L+1} \quad (22)$$

Since the bit error rate is generally substantial in wireless ad hoc networks, this means that there is an optimum packet length, above which the throughput decreases. Therefore, the maximum jitter value J_m should be chosen so that packet size does not increase beyond the CSMA optimum, in which case the throughput would in fact decrease because of the link layer. In that respect, the choice of an appropriate J_m (with respect to out-packet size variation) also depends on λ_{in} and λ_g , as shown in *Proposition 3*.

6 Simulations

This section presents simulation results that focus on the two main results obtained in section 4: the delay introduced by jitter in packet forwarding (both the average length of the collecting phase and the average delay between in-packet reception and forwarding), and the relationship between out-packet traffic rate, self-packet traffic rate and in-packet traffic rate when jittering techniques are used. For a better visualization of the impact of the jitter range, each aspect is measured for collecting phases with jitter values $T = \frac{J_m}{2}$, for different maximum values of the jitter, J_m . Results are presented for a range $0 \leq T \leq 0.5 \text{ sec}$, or equivalently, $0 \leq J_m \leq 1 \text{ sec}$, and directly compared with the corresponding analytical results that were derived in section 4. The simulations were carried out in Maple and the presented results are averaged over 30 iterations per value. 95% confidence intervals are indicated in the figures.

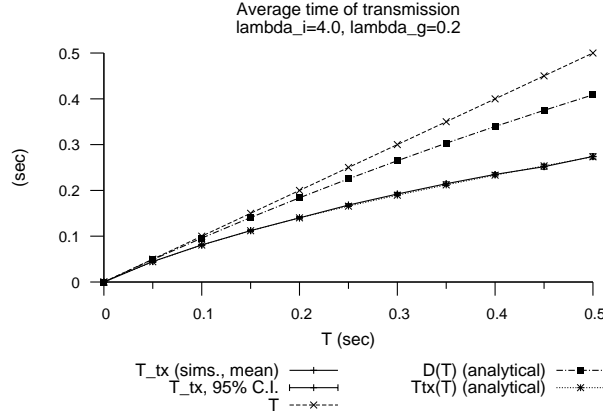


Figure 7: Average time to transmission for $\lambda_{in} = 4 \frac{pkt}{s}$, $\lambda_g = 0.2 \frac{pkt}{s}$, for different values of t (simulations and analytical results).

Figure 7 presents the average delay for an in-packet, $T_{tx}(T)$, the average duration $D(T)$ of the collecting phase (which corresponds to the delay for the triggering in-packet of the phase), together with the averaged results from the simulations. It can be observed that the obtained analytical results are consistent with the simulation results. This suggests that, with the simulated values, the transmission time of in-messages is frequently determined by the jitter values assigned to in-messages previously arrived, and the event that an in-packet arrival follows an out-packet transmission is rare. The probability of such event may increase when in-packet traffic rate decreases, thus approaching the measures of average in-packet delay, $T_{tx}(T)$, to the length of the collecting phase, $D(T)$.

Figure 8 displays the in-packet and out-packet rates obtained in simulations for different values of T , with a nominal in-packet rate of $\lambda_{in} = 4 \frac{pkts}{sec}$ and self-packet rate of $\lambda_g = 0.2 \frac{pkts}{sec}$. Simulations are compared with the out-packet rate provided by the theoretical model via expression (16). It can be observed that the out-packet rate for $T = 0$ corresponds to $\lambda_{in} + \lambda_g = 4 + 0.2 \frac{pkts}{sec} = 4.2 \frac{pkts}{sec}$. For non-zero average values of jitter, the out-packet rate decreases significantly as T grows. The slope of this decrease becomes lower (in absolute terms) as T value

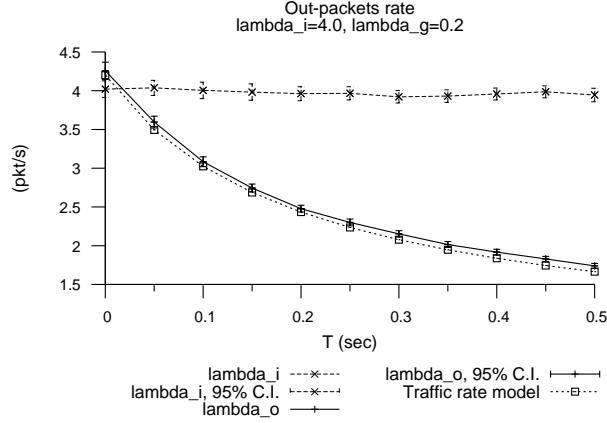


Figure 8: Out-packet (λ_{out}) and in-packet (λ_{in}) rates, for different values of T , and a theoretical in-packet rate $\lambda_{in} = 4 \frac{pkt}{s}$ (simulations and analytical results).

is higher. Although the range of simulated t is not long enough, the observed evolution is consistent with the horizontal asymptote at $\lambda_{out} = \lambda_g = 0.2 \frac{pkt}{sec}$, described in *Proposition 4*.

7 Conclusion

Recurrent network-wide packet dissemination may lead to systematic wireless collisions when performed over wireless multi-hop ad hoc networks. Jittering, a distributed technique based on the schedule of random backed-off transmissions, aims at avoiding such transmissions bound to be synchronized otherwise. Jittering is moreover used to aggregate several packets (those received and buffered while waiting for the next backed-off transmission that has been scheduled) into a single transmission. Reducing the number of transmissions and the number of concurrent transmissions is very desirable in wireless ad hoc networks, where bandwidth is scarce, and energy supply often limited. However, the benefits of jitter come at the price of additional delays, and longer transmissions. This memorandum introduced a model and analysis of standard jittering as specified by the IETF, and derived results on three key aspects: (i) incurred additional delays, (ii) increase in packet size and (iii) reduction in the number of transmissions. This memorandum also presented an analysis of the use of jitter in practice, in conjunction with CSMA, the mechanism on which is based most current link layer technologies, such as 802.11. The analytical results are then validated via simulations. This memorandum thus provides a rather comprehensive analysis of the impact of standard jittering in today's wireless ad hoc networks. Future work will aim at extending the model to consider non-instantaneous packet transmissions, as well as a network-based approach (instead of the interface-based approach used so far) which may capture finer network-wide behavior.

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