Spectrum Sharing Under The Asynchronous UPCS Etiquette: The Performance Of Collocated Systems Under Heavy Load

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1. Abstract

Recently the FCC opened three 10 MHz bands for unlicensed use. In order to operate in UPCS bands, devices must comply with rules known as the UPCS etiquette [1]. In this paper we study channel sharing between two or more collocated systems under the asynchronous UPCS etiquette. In particular we show that under heavy load individual systems have a tendency to hold the channel for hundreds of milliseconds, thus blocking all traffic in other, competing systems. We have calculated the distribution of the blocking time for two versions (or interpretations) of the UPCS etiquette. The impact of the average blocking time on delay sensitive traffic is discussed and possible improvements achieved through a tradeoff between system capacity and average blocking time are investigated.

2. Introduction

The case of several collocated but non-interworking networks is of high importance for the UPCS industry. One of the parameters of interest is the distribution of the blocking time for a system. In the case of two neighboring networks, channel usage alternates between the two systems. If one system is transporting time-sensitive traffic it is important to know the distribution of the blocking period length. In the following analysis we derive this distribution for the case of the two systems, assuming that each one is under heavy load, i.e. a new burst of 10 msec is always waiting to be transmitted. The analysis is carried out for the two interpretations of the etiquette, namely the "nonpersistent" and the "1-persistent" versions. To the best of our knowledge the nonpersistent version has been adopted as an official interpretation of [1].

3. Model

The asynchronous UPCS etiquette belongs to the Carrier Sensing (CS) or Listen-before-talk (LBT) family of multi-access schemes [2]. The basic assumptions are that the channel assessment is not instantaneous and that the maximum period of time a user or a cooperating group of users can transmit uninterrupted is 10 milliseconds. Before each transmission, a user monitors the channel for 50 microseconds. If, during this interval, the power on the channel never exceeded a predefined deference threshold, then the node has permission to transmit. It is assumed here that after successful monitoring, the node can start transmission immediately although, in practice, a turnaround time needs to be taken into account. If the power exceeded the deference threshold the node can follow one of two courses, both of which have been promoted as desirable interpretations of Part 15(d). In the first, which we have labeled as the nonpersistent case, the node defers a random amount of time, called the deference interval, and repeats the monitoring procedure. In the other case, which we call 1-persistent with collision avoidance, the node continuously monitors the channel (i.e., repeats the monitoring procedure) until it detects channel idle (i.e., power below threshold for 25 consecutive microseconds), upon which it can start a random deference interval. In the following text we shall refer to the latter scheme as simply 1-persistent having in mind that a transmission is delayed a random time interval after the channel becomes clear.

The range from which the uniformly distributed deference interval is chosen is doubled each time a node detects channel busy. The lower limit is fixed at 0.050 msec while the upper limit is initially 0.75 milliseconds (before the first attempt) and reaches the upper limit of 12 msec after four unsuccessful tries. After reaching this upper limit the deference interval is kept constant indefinitely. This is in contrast to Ethernet's (IEEE 802.3) retransmission scheme where retransmissions are aborted after 16 tries [3]. After completing a transmission, a node waits additional interval before it can transmit any new packets.

The etiquette does not specify the way acknowledgments are delivered. We have assumed that the ACKs are very short packets sent after a short gap by the destination node without the LBT procedure. A system or a cooperating group of users can keep the channel up to 10 msec without further LBT provided that the interpacket gap is less than 25 μsec.

In the analysis presented below we consider two systems competing for the channel under heavy load. Each system monitors the channel after a random deference interval (as mentioned above) following the previous end of transmission (1-persistent case) or an unsuccessful 50 microsecond monitoring event (nonpersistent case). If the channel is sensed clear a series of packets is transmitted by units within the winning system for 10 msec. If the first packet sent by system A (Fig. 1) is detected by system B then all subsequent packets sent in the same 10 msec window will be detected. We have assumed that packet transmission within each system is controlled by a MAC of choice, the details of which are of no importance to us as long as the interpacket gap is less than 25 μsec. A sequence of transmission cycles, each consisting of a busy period followed by an idle period, is shown in Fig. 1.

In practical situations a collision can occur due to either partial connectivity between the systems or a non-zero radio turnaround

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time. In the analysis we assume that collision probability is negligible. We shall discuss this in Section 5.

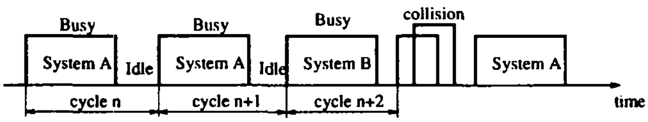

Figure 1. A sequence of transmission cycles in a case of two collocated systems.

Collisions tend to decrease the blocking time since the deference time limits are reset after every transmission, both successful and unsuccessful.

Assume that a system, A, following the nonpersistent etiquette has just lost contention as shown in Fig. 2. A series of channel monitoring periods will follow separated by random time intervals. The first delay is chosen from a uniform distribution U(0.05,1.5), times being expressed in msec. In defining the intervals of random length the following notation is used

$$X_T, Y_T \sim U(0.05, T), \quad T \in \{0.75,\ 1.5,\ 3,\ 6,\ 12\}.$$

After four unsuccessful monitoring periods, each time doubling the upper limit, the system starts choosing the delay from the uniform distribution U(0.05, 12) msec. Thus, after the interval X_6 (Fig. 2) the deference process is a renewal process. To simplify the assumptions, we assume that the renewal process starts during the first transmission period and that the renewal process is in "steady-state" at the end of the first busy period of the blocking time. It will also be assumed that the end of 10 msec busy periods are independent of the deference renewal process. We justify these assumptions by simulation.

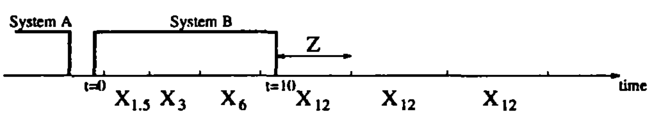

Figure 2. A sample path of the deference renewal process in the nonpersistent etiquette.

4. Analysis

In this section we derive the probability mass function and the average length of the blocking period for the nonpersistent and 1-persistent UPCS etiquette. First we focus on the nonpersistent case.

Let us assume that at time t = 0 one system, B, wins contention after being blocked for one or more transmission cycles. At time t = 10 system B stops transmission and draws a deference delay from a uniform distribution U(0.05,0.75). We need the distribution of the time interval from the time the channel becomes clear (i.e., t=10) until the blocked system A is scheduled to monitor the channel. Denote this interval as a random variable Z (Fig. 2). From our assumptions in Section 3 random variable Z represents the excess life of the deference renewal process [4]. The steady state distribution of Z is given by [4]

$$f_Z(z) = \begin{cases} 0 & z < 0 \\ \dfrac{1 - F_{X_{12}}(z)}{E[X_{12}]} & 0 \le z \le 12 \\ 1 & z > 12. \end{cases} \tag{1}$$

where $F_{X_{12}}(z)$ is the cumulative distribution function of X_{12}. As before all times are expressed in msec. The probability that the blocked system, A, will win the next contention round is given by

$$P[X_{0.75} > Z] = \iint_{\Omega} f_{X_{0.75}Z}(x,z)\,dx\,dz \tag{2}$$

where $\Omega = \{(x,z): x > z\}$. Since $X_{0.75}$ and Z are independent we have that

$$P[X_{0.75} > Z] = \int_{z=0}^{12} \int_{x=z}^{0.75} f_{X_{075}}(x) f_Z(z)\,dx\,dz. \tag{3}$$

After performing the integration we obtain $P[X_{0.75}>Z]=p=0.06525$, where p is the probability that the channel will "change hands" at the end of each transmission cycle. Thus, the probability that one system will be blocked for $N_b=k$ transmission cycles is given by

$$P[N_b = k] = p(1-p)^{k-1} \qquad \text{for } k \ge 1 \tag{4}$$

and the average length of the blocking period in the case of nonpersistent UPCS expressed in the number of transmission cycles is given by

$$E[N_b] = \frac{1}{p} = 15.324. \tag{5}$$

In order to find the average blocking period expressed in msec we need to obtain the average cycle period. The average idle period E[I] is equal to the expected value of the random variable $X_{0.75}$ conditioned on the event that $\{X_{0.75}<Z\}$, except in the case of the last idle period L whose average idle period is equal to $E[Z| X_{0.75}>Z]$. Thus,

$$\begin{aligned} E[L] &= E[Z | X_{075} > Z] \\ &= \frac{\int_{x=0}^{0.75} \int_{z=0}^{x} z f_{X_{075}}(x) f_Z(z)\,dx\,dz}{P[X_{075} > Z]} \\ &= 0.248452 \end{aligned} \tag{6}$$

and

$$E[I] = E[X_{075} | X_{075} < Z]$$
$$= \frac{\int_{x=0}^{0.75} \int_{z=x}^{12} x f_{X_{075}}(x) f_Z(z) dx dz}{P[X_{075}<Z]} \quad (7)$$
$$= 0.392962.$$

It is interesting to note that the average value of the last idle period is significantly smaller than the preceding idle periods. The reason for this is that the random variable Z is more concentrated around the origin and that Z is conditionally bounded by a smaller value, $X_{0.75}$. Finally, the average length of the blocking period is given by,

$$E[T_b] = (E[N_b]-1)E[I] + E[N_b]10 + \\ + E[L] = 159.121. \quad (8)$$

The details of the calculation of the 1-persistent version are presented in the Appendix. The analysis above assumes that two systems with zero turnaround time radios are competing for the channel. One extension would be to increase the number of competing systems to M>2. In that case (M-1) blocked systems are trying to take over the channel from the "incumbent" system. The blocked system with the shortest deference time Z will compete with the currently transmitting system. The distribution in (1) needs to be modified to represent the distribution of the minimum of (M-1) iid random variables each having the distribution as in (1). With this distribution the analysis follows the same logic as in (2)-(7). It is clear that any of the (M-1) blocked systems can win the contention with equal probability.

5. Simulation results

It is assumed in the simulation that each 10 msec burst consists of a large number of short packets exchanged within each system. If the first packet is not received the burst is interrupted and the system defers a random interval drawn from U(0.05,0.75). In this way the system can detect collision early on and reschedule the next attempt. The blocking period includes the waiting period until the start of the successful burst.

Figure 3. shows the average blocking time as a function of the radio receive-to-transmit turnaround time in a two-system UPCS scenario. Our analytical results correspond to the case of zero turnaround time. It can be noted that the analytical results match well the simulation. Longer turnaround times mean that the monitoring procedure provides more outdated information about the channel status. The increase in the turnaround time increases the probability of collision which forces the nodes to reset their deference time limits. Note that a system continues to be blocked until it has successfully acquired the channel. It would seem that collisions will increase the probability that the blocked system wins contention. However, the effect of increased collision rate appears to have no impact on the average blocking period up to 50 μsec turnaround time. If the blocking time is defined as the interval until the blocked system transmits for the first time the curves in Fig. 3 would have a slight negative slope. We have chosen 50μsec in Fig. 3. since longer radio turnaround times were shown to decrease the channel capacity significantly [5].

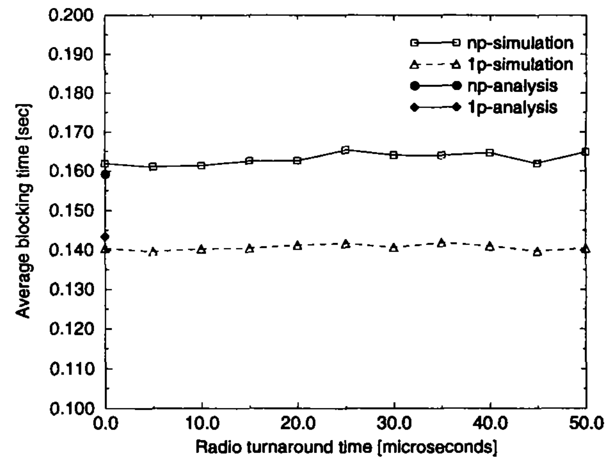

Figure 3. Average value of the blocking time as a function of the radio turnaround time. Analytical results are included for the case of zero turnaround time.

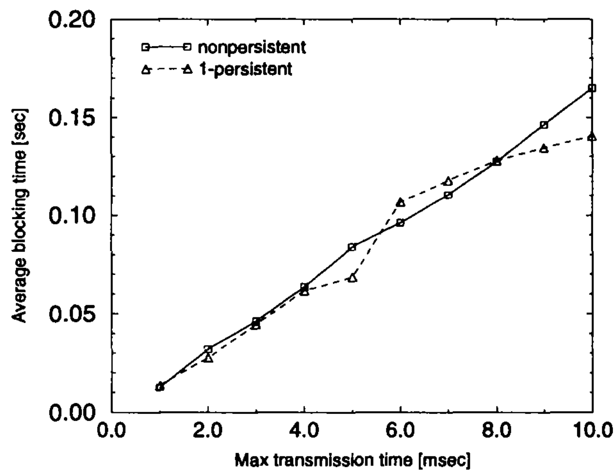

Figure 4. The average blocking time as a function of the maximum transmission time obtained by simulation. The radio turnaround time is fixed at 50 μsec.

The effect of the maximum transmission time on the average blocking time is shown in Fig. 4. The etiquette allows a maximum channel occupancy of 10 msec. In the simulations we have retained all the deference rules the same as prescribed by [1]. The radio turnaround time was fixed at 50 μsec. The average blocking time decreases roughly linearly reaching the value of ~ 13 msec for the maximum transmission time of 1 msec both for the nonpersistent and 1-persistent etiquette. It can be shown [5] that for a large number of competing nodes the two versions of the etiquette do not differ in terms of delay performance. Since the nonpersistent version allows users to spend more time in the sleep mode it is considered more favorable. In Fig. 5 we show that the decrease in blocking time comes with a price, namely in decreased channel throughput, which both systems equally share. Even for transmission time of 1 msec, when each system has approximately

33% of the maximum channel throughput, the probability that the blocking time is greater than 50 msec is approximately 5% (equation (4)). This shows that it is questionable if the asynchronous UPCS etiquette can guarantee delivery of time sensitive traffic, such as for example voice traffic.

It should be noted that in the analysis and the simulation we have assumed that only two systems contend in the same way as two users would contend for the channel in UPCS. If, however, more users from each of the two systems we allowed to contend for the channel we expect the blocking time per system to decrease.

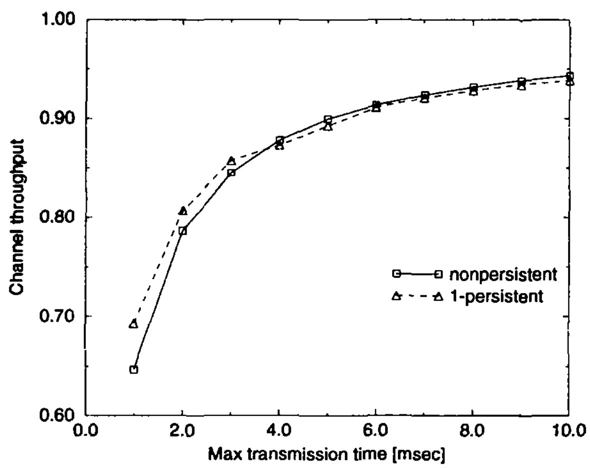

Figure 5. The normalized channel throughput as a function of the maximum transmission time obtained by simulation. The radio turnaround time is fixed at 50 µsec. The throughput is shared equally over long time periods between the two competing systems.

6. Discussion

In this paper we have presented analytical and simulation results of the blocking time in a two system Asynchronous UPCS etiquette. We have shown that presently the UPCS etiquette allows one system to be blocked for approximately 160 msec on the average. This is clearly unacceptable for voice transmission and other delay sensitive traffic. With some simple changes, such as reducing the maximum transmission time from 10 msec to 1 msec, the average blocking time is decreased as well; however, long blocking times still occur with non-negligible probability. Some of the lessons learned from the design and analysis of the UPCS etiquette will be useful for the design of the future rules of spectrum sharing. Clearly, more work is needed for better understanding of the design of fair etiquettes that guarantee bounded blocking time.

7. Appendix

We now analyze the 1-persistent UPCS etiquette. A sample path of the protocol is shown in Fig. 6. As we have already noted, if the channel was detected busy during the monitoring interval the blocked system (B) continues to monitor the channel until it becomes clear. At this time a random deference period is scheduled. Each time a system detects a busy channel the upper limit of the deference time is doubled starting from 0.75 up to the value of 12 (msec).

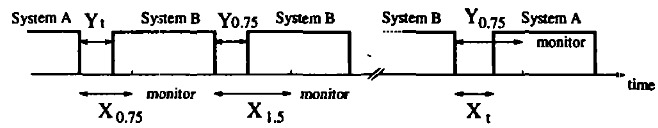

Figure 6. A sample path of the 1-persistent version of the etiquette. System A observes the channel busy and continues to monitor until system B stops transmitting. At that time system A defers for a random period $X_{1.5}$.

Assume that shortly before time t=0 a busy period ends and that in the next transmission cycle (following the idle period at t=0) system B wins contention. Shortly before t=0 system A has drawn its deference interval from the distribution U(0.05,0.75). Since busy periods last 10 msec system A must have started monitoring during the first busy period. Thus, the probability that system A schedules monitoring during the first busy period p_1 is equal to 1. At the end of the first busy period (B's transmission) system A draws a new deference interval from the distribution U(0.05,1.5). The probability that system A starts monitoring during the second busy period is equal to the probability that it will lose contention after the first transmission cycle, i.e.

$$\begin{aligned} p_2 &= p_1 P[X_{1.5} > Y_{075}] \\ &= p_1 \int_{y=0}^{0.75} \int_{x=y}^{1.5} f_{Y_{075}}(y) f_{X_{075}}(x) dx dy = 0.758621 \end{aligned} \tag{9}$$

Similarly, we have the probabilities of system A scheduling monitoring during the 3rd, 4th and the 5th busy period given by

$$\begin{aligned} p_3 &= p_1 p_2 P[X_3 > Y_{075}] = 0.668615 \\ p_4 &= \prod_{i=1}^{3} p_i P[X_6 > Y_4] = 0.629285 \\ p_5 &= \prod_{i=1}^{4} p_i P[Y_{075} < X_{12} < Y_{075} + 10] = 0.526598. \end{aligned} \tag{10}$$

At the end of the k-th (k≥4) busy period system A starts drawing deference periods from the distribution U(0.05,12). It is possible for system A to schedule the next monitoring during the (k+1)-th and (k+2)-th busy period, where k≥ 4. Thus, we can express the probability of monitoring during the (k+2)-th interval as follows

$$p_{k+2} = bp_k + ap_{k+1} \tag{11}$$

for k≥ 4, and where

$$a = P[Y_{075} < X_{12} < Y_{075} + 10] = 0.83682$$

$$b = P[X_{12} > Y_{0.75} + 10 + Y'_{0.75}] = 0.100418. \tag{12}$$

The solution of the difference equation (11), which uses the initial conditions p_4 and p_5, is given by

$$p_k = Aq_1^{k-4} + Bq_2^{k-4} \tag{13}$$

where $k \geq 4$. The constants are $A \cong 0.565457$, $B \cong 0.0638178$, $q_1 \cong 0.943277$ and $q_2 \cong -0.106457$. Note that $\sum_{k=1}^{\infty} p_k > 1$ due to the way the probabilities p_k are defined, e.g. the event that monitoring is scheduled during the k-th transmission cycle does not exclude the event that monitoring is scheduled during the (k+1)-st transmission cycle.

Assume that system A monitors the channel during the k-th busy period. Then the probability that it wins contention in the (k+1)-st transmission cycle is given by

$$c = P[X_{12} < Y_{0.75}] = 0.0292887. \tag{14}$$

Similarly, the probability that system A wins contention in the (k+2)-th transmission cycle after the latest monitoring in the k-th busy period is given by

$$\begin{aligned} d &= P[Y_{0.75} + 10 < X_{12} < Y_{0.75} + 10 + Y'_{0.75}] \\ &= 0.0334728. \end{aligned} \tag{15}$$

The probability that the blocking period lasts k transmission cycles is given by

$$r_k = dp_{k-1} + cp_k, \tag{16}$$

where $k \geq 5$. For $k<5$ we have the following expressions

$$\begin{aligned} r_1 &= p_1 P[X_{1.5} < Y_{0.75}] \\ &= p_1 \int_{y=0}^{0.75} \int_{x=0}^{y} f_{X_{075}}(x) f_{Y_{075}}(y) dx dy = 0.241379 \\ r_2 &= p_2 P[X_3 < Y_{0.75}] = 0.09 \\ r_3 &= p_3 P[X_6 < Y_{0.75}] = 0.03933 \\ r_4 &= p_4 P[X_{12} < Y_{0.75}] = 0.01843. \end{aligned} \tag{17}$$

Note that the probability that blocking will last for one transmission cycle is four times higher than in the case of nonpersistent etiquette (equation (3)). However, r_i's decrease faster than the probabilities in (4) (the PMF of the r_i's has a longer tail). The average number of transmission cycles spent in the blocked state is given by

$$\begin{aligned} E[N_b] &= \sum_{k=1}^{\infty} kr_k = \sum_{k=1}^{4} kr_k + \sum_{k=5}^{\infty} k(cp_k + dp_{k-1}) \\ &= \sum_{k=1}^{3} kr_k + \sum_{k=4}^{\infty} (k+1)dp_k + \sum_{k=4}^{\infty} kcp_k \\ &= \sum_{k=1}^{3} kr_k + (c+d) \sum_{k=4}^{\infty} kp_k + d \sum_{k=4}^{\infty} p_k \\ &= 13.8175 \end{aligned} \tag{18}$$

We denote the idle period after the k-th busy period as I_k, except in the case when the blocked system wins contention in the (k+1)-st transmission cycle. In the latter case we denote the last idle period as L_k. Thus, the total blocking time can be expressed as follows

$$T_b = 10N_k + \sum_{i=1}^{N_b-1} I_i + L_{N_b}. \tag{19}$$

Now we calculate the expected values of I_k and L_k from the equation (19). The L_k is the last idle period during the blocking period while the I_k's are regular idle periods.
The average values of I_k can be calculated as

$$\begin{aligned} E[I_1] &= E[Y_{0.75} | Y_{0.75} < X_{1.5}] \\ &= \frac{1}{P[Y_{0.75} < X_{1.5}]} \int_0^{0.75} \int_y^{1.5} y f_{Y_{075}}(y) f_{X_{15}}(x) dx dy \\ &= 0.362879. \end{aligned} \tag{20}$$

The idle periods I_2, I_3 and I_4 are calculated in a similar way as in (21). Thus, we obtain

$$\begin{aligned} E[I_2] &= E[Y_{0.75} | Y_{0.75} < X_3] = 0.384295 \\ E[I_3] &= E[Y_{0.75} | Y_{0.75} < X_6] = 0.392703 \\ E[I_4] &= E[Y_{0.75} | Y_{0.75} < X_{12}] = 0.39648. \end{aligned} \tag{21}$$

For $k \geq 5$ a slightly different expression is used,

$$\begin{aligned} E[I_k]|_{k\geq 5} &= \frac{a}{a+b} E[Y_{0.75} | Y_{0.75} < X_{12} < Y_{0.75} + 10] + \\ &\quad + \frac{b}{a+b} E[Y'_{0.75} | Y_{0.75} + 10 + Y'_{0.75} < X_{12}] \\ &= \frac{a}{a+b} \frac{1}{P[Y_{0.75} < X_{12} < Y_{0.75} + 10]} \times \\ &\quad \int_0^{0.75} \int_y^{y+10} y f_{X_{12}}(x) f_{Y_{075}}(y) dx dy + \end{aligned}$$

$$+\frac{b}{a+b}\frac{1}{P[Y_{0.75}+10+Y'_{0.75}<X_{12}]}\times$$
$$\int_0^{0.75}\int_0^{0.75}\int_{y+10+z}^{12} y f_{X_{12}}(x) f_{Y_{075}}(y) f_{Y'_{075}}(z)\,dx\,dy\,dz$$
$$=0.393211 \tag{22}$$

where a and b are defined in (12). Similarly, we calculate the expected values of L_k

$$E[L_1]=E[X_{1.5}|Y_{0.75}>X_{1.5}]$$
$$=\frac{1}{P[Y_{0.75}>X_{1.5}]}\int_0^{0.75}\int_0^{y} x f_{X_{15}}(x) f_{X_{075}}(y)\,dx\,dy$$
$$=0.2833 \tag{23}$$

and similarly for in the case of L_2, L_3 and L_4. Finally, for $k\geq 5$ we obtain

$$E[L_k]|_{k\geq 5}=\frac{a}{a+b}E[X_{12}|Y_{0.75}>X_{12}]+$$
$$+\frac{b}{a+b}E[X_{12}-Y_{0.75}-10|$$
$$=\frac{a}{a+b}\frac{1}{P[Y_{0.75}>X_{12}]}\times$$
$$\int_0^{0.75}\int_0^{y} x f_{X_{12}}(x) f_{Y_{075}}(y)\,dx\,dy$$
$$+\frac{b}{a+b}\frac{1}{P[Y_{0.75}+10<X_{12}<Y_{0.75}+10+Y'_{0.75}]}$$
$$\times\int_0^{0.75}\int_0^{0.75}\int_{y+10}^{y+10+z}(x-10-y) f_{X_{12}}(x) f_{Y_{075}}(y)$$
$$f_{Y'_{075}}(z)\,dx\,dy\,dz$$
$$=0.2833. \tag{24}$$

Thus, it turns out that $E[L_k]=0.2833$ for all $k=1,2\ldots$. This should not be surprising since L_k's are positive uniform random variables conditionally smaller than a uniform variable with a smaller range ($X_{0.75}$).

The average length of the blocking period is given by

$$E[T_b]=10E[N_k]+E[\sum_{i=1}^{N_b-1}I_i]+E[L_{N_b}]$$
$$=10E[N_k]+\sum_{k=1}^{\infty}(\sum_{i=1}^{k-1}E[I_i])r_k+\sum_{k=1}^{\infty}E[L_k]r_k$$
$$=143.391. \tag{25}$$

The 1-persistent version has approximately 10% smaller average blocking time than the nonpersistent version.

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