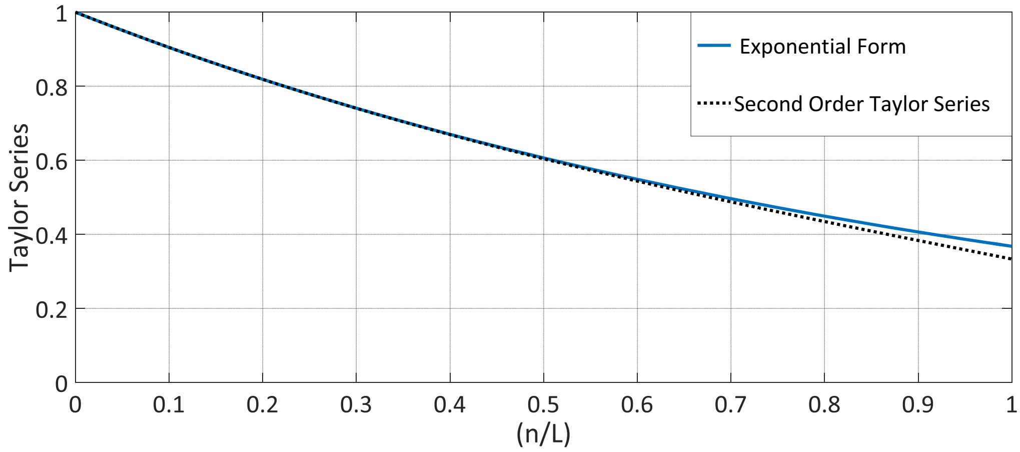


Figure 5.1: Second order Taylor series approximation for $e^{-\frac{1}{\beta}}$, where $\beta = \frac{L}{n}$

in:

$$\{t_e E + t_c C\} \frac{\partial}{\partial L}(S) = S \frac{\partial}{\partial L} \{t_e E + t_c C\} \tag{5.5}$$

Then, substituting the values of E, S, and C from (3.1) leads to:

$$\begin{aligned} &\left\{ t_e \underbrace{L\left(1-\frac{1}{L}\right)^n}_{E} + t_c \underbrace{\left(L - \left(1-\frac{1}{L}\right)^{n-1}(L-n-1)\right)}_{C} \right\} \\ &\qquad \times \frac{\partial}{\partial L} \underbrace{n\left(1-\frac{1}{L}\right)^{n-1}}_{S} \\ &\qquad = \underbrace{n\left(1-\frac{1}{L}\right)^{n-1}}_{S} \\ &\times \frac{\partial}{\partial L} \left\{ t_e \underbrace{L\left(1-\frac{1}{L}\right)^n}_{E} + t_c \underbrace{\left(L - \left(1-\frac{1}{L}\right)^{n-1}(L-n-1)\right)}_{C} \right\} \end{aligned} \tag{5.6}$$

By simplifying the result, the final exact equation for the proposed time-aware frame length is given by the implicit equation:

$$\left(1 - \frac{n}{L_{TA}}\right) = (1 - C_t)\left(1 - \frac{1}{L_{TA}}\right)^n, \tag{5.7}$$

where n is the number of tags, and C_t is the slot duration constant defined

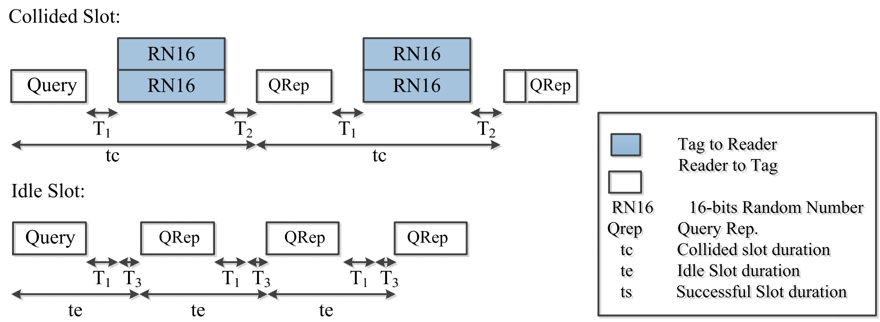


Figure 5.2: Slot durations during tag inventory rounds for the ISO 18000-6C standard

5.1.2 Slot Duration Constant Calculation For the EPCglobal C1 G2

In this section, the calculation method of the slot duration constant C_t from the physical layer parameters will be discussed. Figure 5.2 shows the timings of collided and empty slots. Each slot contains different sequences of reader to tag commands and tag replies. Based on the EPCglobal C1 G2 standard [11], the slot duration constant is

$$C_t = \frac{t_e}{t_c}, \tag{5.14}$$

As shown in figure 5.2, the empty slot duration t_e is given by:

$$t_e = T_{QRep} + T_1 + T_3. \tag{5.15}$$

Here, T_{QRep} is the query repeat command time:

$$T_{QRep} = T_{FS} + T_{command}, \tag{5.16}$$

with, $T_{FS} = 3.5 \cdot T_{ari}$, $T_{command} = 6 \cdot T_{ari}$, and $T_{ari} = \frac{DR}{2.75} T_{pri}$. By substituting in (5.16) we get

$$T_{QRep} = 3.5 \cdot DR \cdot T_{pri}, \tag{5.17}$$

where T_{ari} is reader symbol duration, $T_{pri} = \frac{1}{BLF}$, BLF is the tag backscatter link frequency and DR is the so-called divide ratio constant that can take the two values $DR = 8 \,\text{or}\, \frac{64}{3}$. Finally, M equals to 1, 2, 4, or 8, which represents

Table 5.1: Available slots duration constants C_t of the EPCglobal C1 G2 standards

Divide Ratio: DR	Modulation: M	Pilot Length: n_p	C_t
8	1	0	0.47
		12	0.41
	2	4	0.35
		16	0.28
	4	4	0.23
		16	0.18
	8	4	0.14
		16	0.1
64/3	1	0	0.7
		12	0.65
	2	4	0.57
		16	0.5
	4	4	0.43
		16	0.35
	8	4	0.3
		16	0.22

the modulation types FM0, Miller 2, 4, or 8, respectively. T_1 is the time from the reader transmission to the tag response, which can be expressed as:

$$T_1 = \max\{DR \cdot T_{pri},\, 10 \cdot T_{pri}\} \tag{5.18}$$

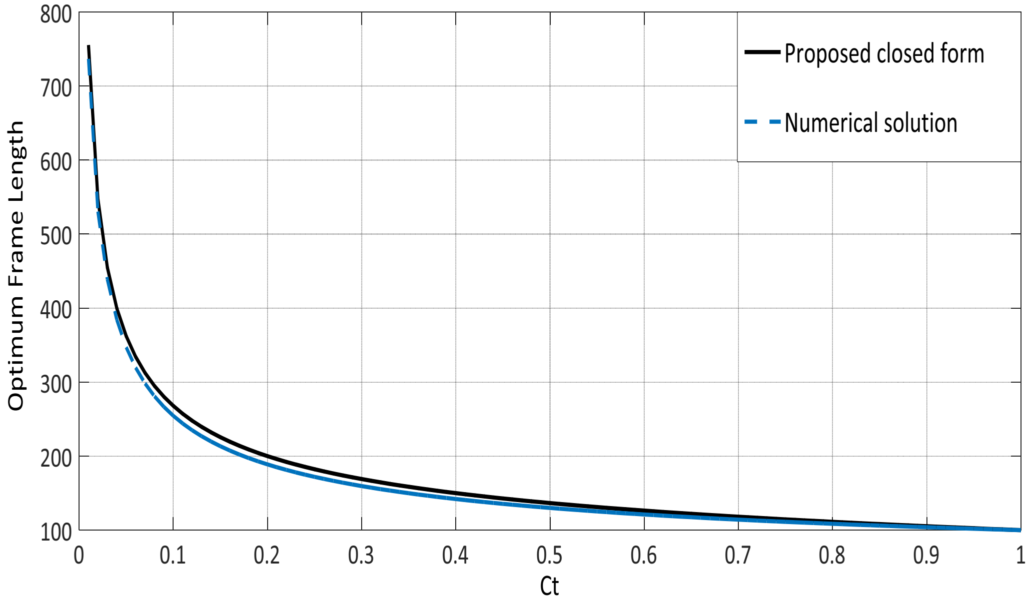
Next, T_3 is the time that the reader waits after T_1 before issuing another command. As it has no constraints, it can be assumed to be zero. After substituting (5.17) and (5.18) in (5.15), t_e can be expressed as:

$$t_e \;=\; T_{pri} \cdot (3.5 \cdot DR + \max\{DR,\, 10\}) \,. \tag{5.19}$$

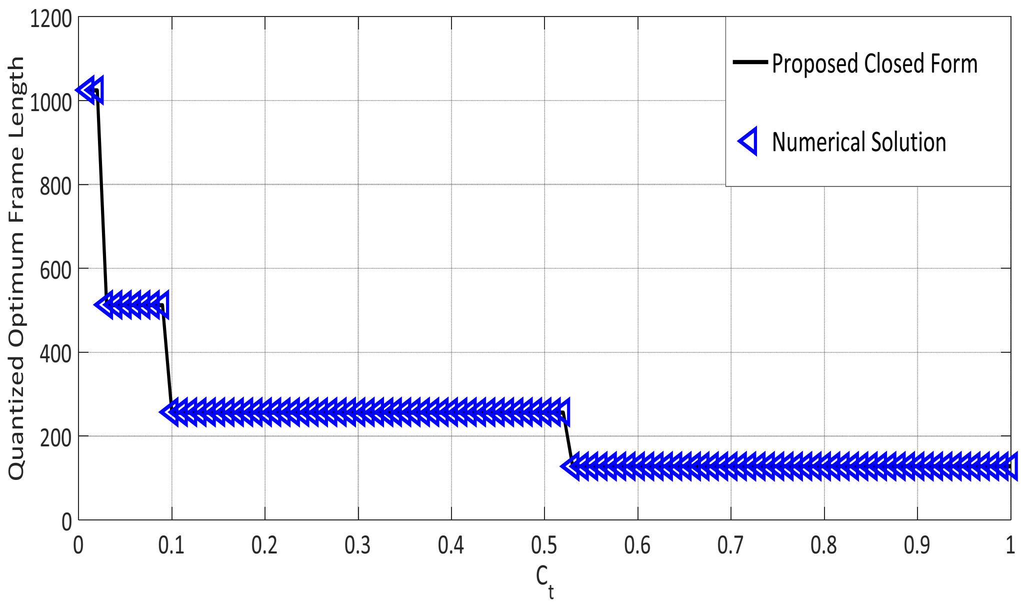
Next, the collided slot duration t_c is given by:

$$t_c = T_{QRep} + T_1 + T_2 + T_{RN16}, \tag{5.20}$$

where T_2 is the reader response time starting from the end of the tag response, $T_2 = 6 \cdot T_{pri}$, and T_{RN16} is the duration of 16 bits temporary data, 6 bits



(a) Non-quantized Frame length



(b) Quantized Frame Length

Figure 5.3: Optimum frame length L_{TA} as a function of the slot duration constant C_t ($n = 100$ tags). The conventional case with identical slot durations corresponds to $C_t = 1$.

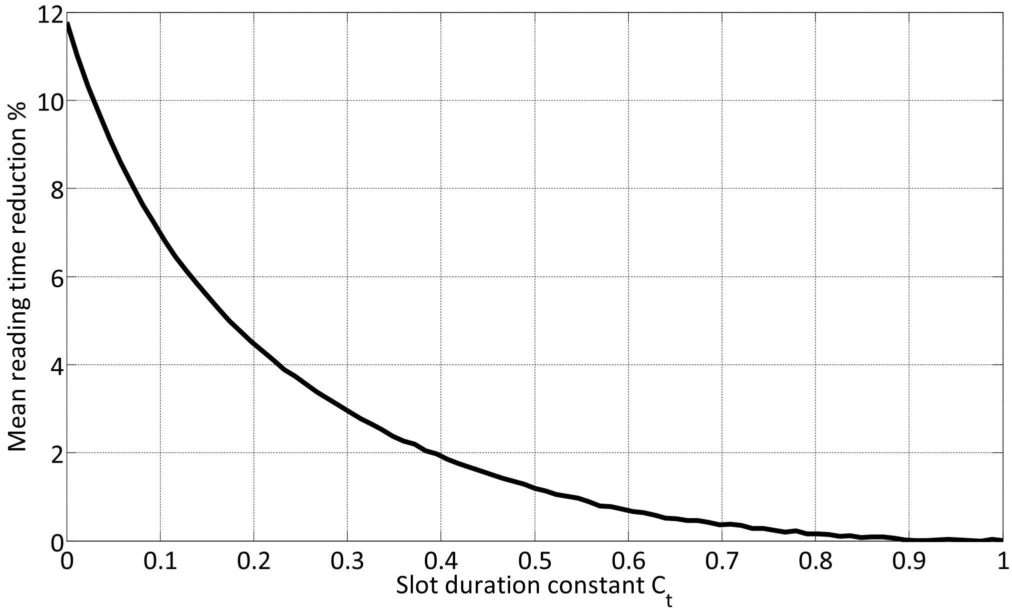


Figure 5.4: Percentages of saving time using the proposed TAFSA for an ideally known number of tags, $C_t = 1$ is the conventional FSA

upon using the proposed ML estimation algorithm. According to figure 5.5, the better estimation algorithms, the less reading time reduction, because it decreases the number of iterations in FSA process. However, using a non-accurate number of tags estimation algorithms, FSA needs more iterations, with more FSA frame length adaptations. That gives more importance for the proposed formula compared to the classical frame length adaptations.

5.2 Time and Collision Recovery System

As mentioned in chapter 4, modern RFID readers are able to decode one of multiple collided tags, which is called the collision recovery capability α. According to the literature we can divide the previous research, which considered the collision recovery capability in the frame length optimization, into three different groups: The first group considered only the average collision recovery probability for the frame length optimizations, such as [58]. The authors proposed a closed form equation for the optimum frame length maximizing the reading throughput per frame. The second group observed only the different

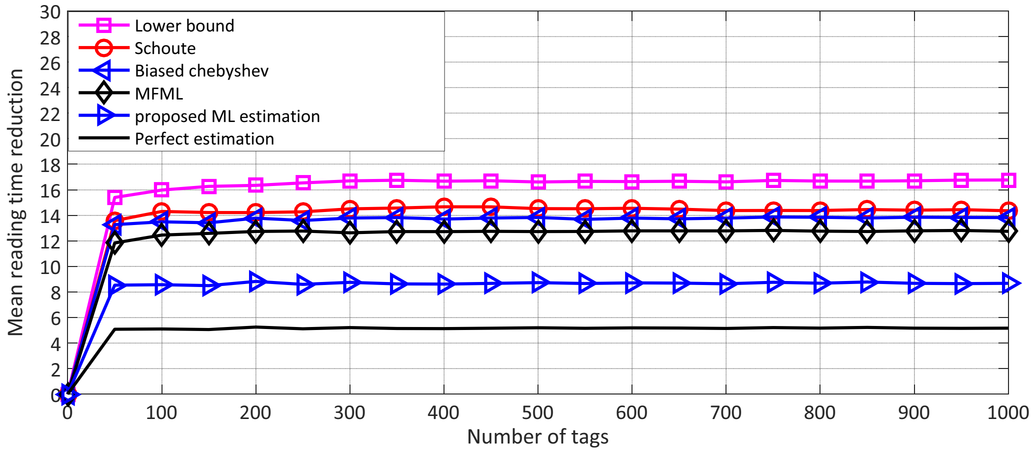
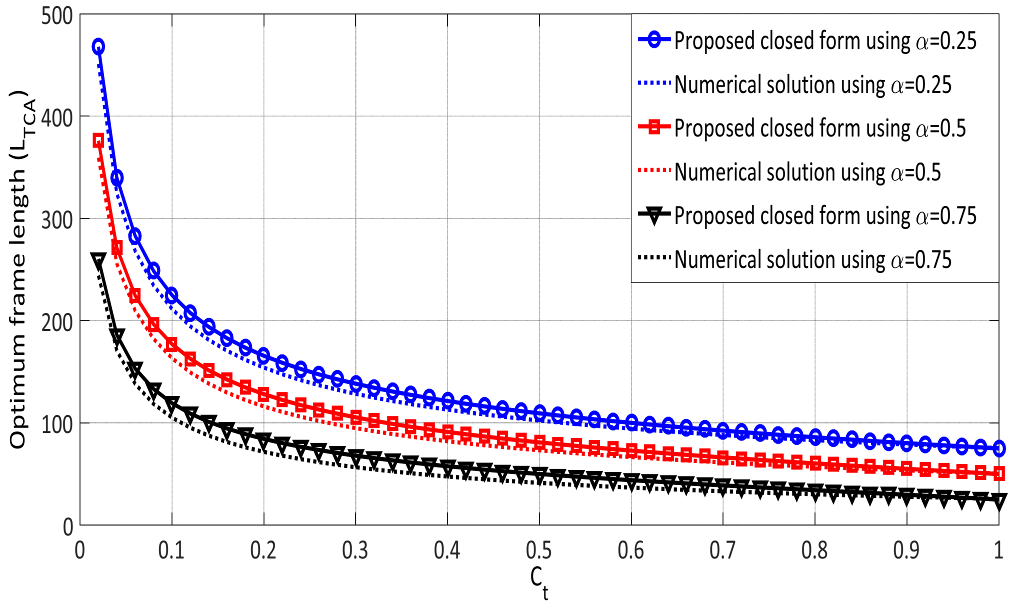


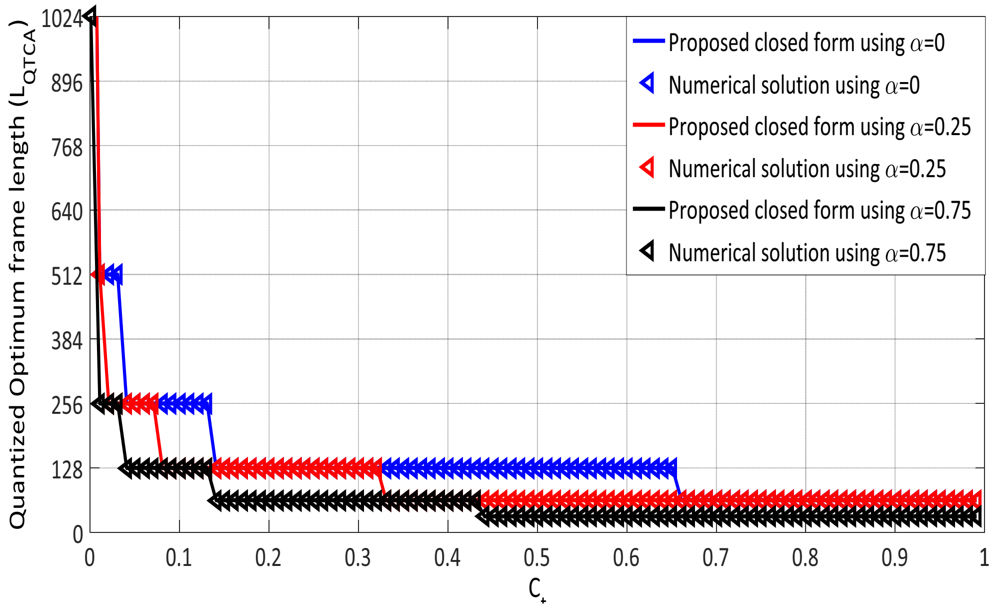
Figure 5.5: Percentages of saving time using the proposed TAFSA compared to the conventional frame length $L = n$ for different anti-collision algorithms using $C_t = 0.2$

slot durations, such as [88, 91] and as shown in the first proposal in the previous section. However, no closed form solution for the optimum frame length was derived. They calculated the optimum frame length numerically. The third group contemplated the different slot durations and the collision recovery probability, such as [86,92,93]. Both [86,92] gave numerical solutions for the optimum frame length versus the collision recovery probability and the number of tags. The main problems of their numerical solutions are the multiple degrees of freedom. The solutions require a complex multidimensional look-up table that has to consider all possible degrees of freedom. [93] uses curve fitting to find a closed form solution for the optimum frame length at a specific collision recovery probability and timing. However, this solution can not be generalized for all values of slot's timing and collision recovery probabilities.

In this section, a closed form solution for the optimum frame length will be derived by optimizing the reading throughput per frame, which does not require any look-up table [86, 92]. In addition, we take into consideration the average collision recovery probability and the different slot durations. Moreover, the calculation method of the collision recovery probability based on the physical layer will be clarified.



(a) Non-quantized Frame Length



(b) Quantized Frame Length

Figure 5.6: Optimum frame length L_{TCA} as a function of the slot duration constant C_t ($n = 100$ tags) for the capture probabilities $\alpha = 0.25$, 0.5, 0.75.

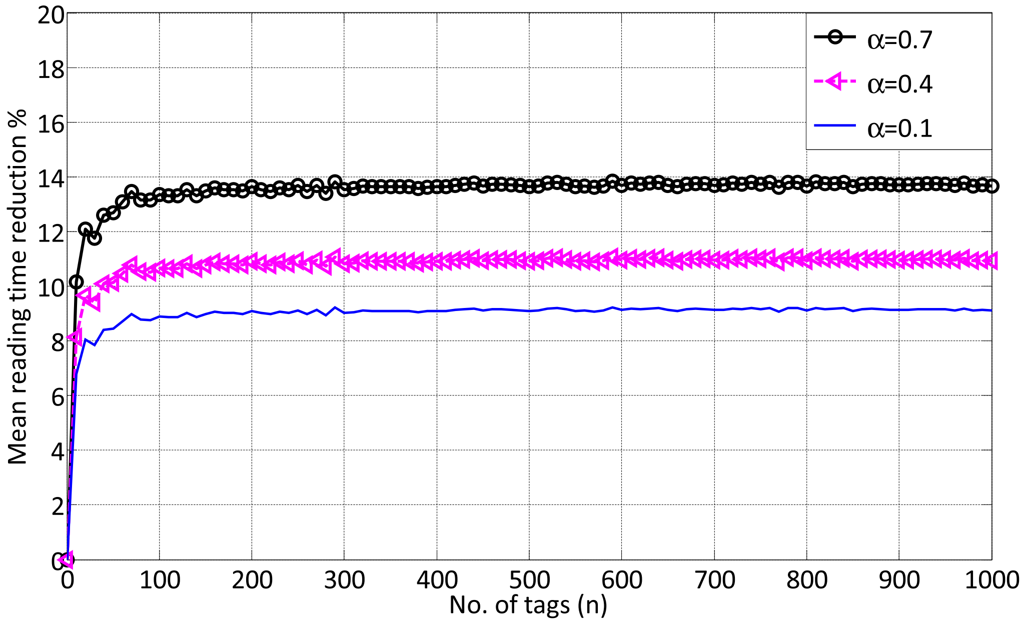


Figure 5.7: Reading time reduction using the proposed TCRA compared to the conventional frame length $L = n$ for perfect number of tags estimation using $C_t = 0.2$ and different values of α

only quantized values (power of 2). Thus, the next quantized frame length is selected and this will eliminate the approximation error. Figure 5.6b shows that the proposed frame length fully match the numerical solution in the full range of C_t.

5.2.3 Mean Reduction of Reading Time

As mentioned previously, the most common performance metric of comparison is the mean reduction in reading time compared to the conventional frame length $L = n$. Figure 5.7 illustrates simulation results for the reading time reduction of the proposed optimal TCRA frame length L_{TCA} wrt. the classical optimal frame length $L = n$ for $C_t = 0.2$ and different values of the collision recovery probability α. These simulations assume a perfect knowledge of the number of tags n. According to figure 5.7, the mean reading time reduction increases when the value of α increases, which gives more advantage to the proposed solution compared to the conventional one.

Figure 5.8 shows the mean reduction of the reading time using the proposed

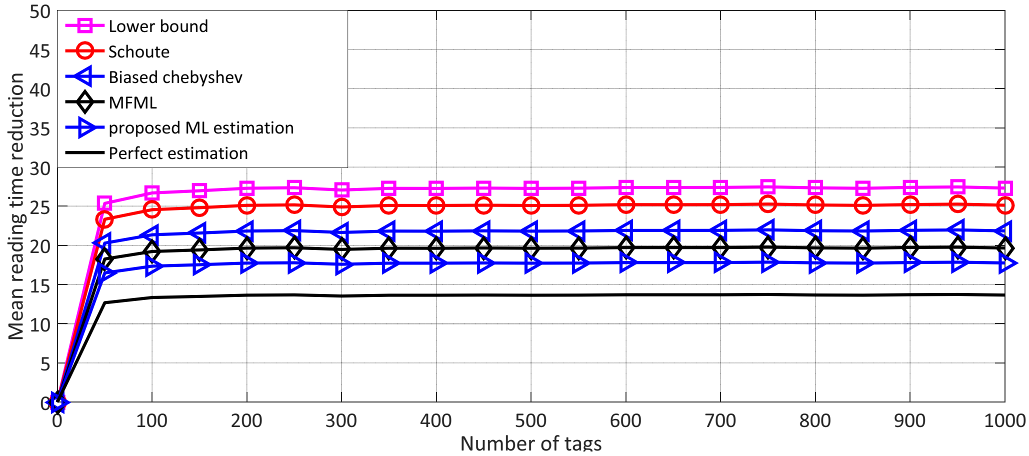


Figure 5.8: Percentages of saving time using the proposed TCRA compared to the conventional frame length $L = n$ for different anti-collision algorithms using $C_t = 0.2$ and $\alpha = 0.6$

TCRA frame length compared to the conventional frame length $L = n$ taking into consideration the effect of the number of tags estimation algorithms. According to figure 5.8, the minimum mean reading time reduction is obtained upon having perfect knowledge of the number of tags in the reading area, because it results in the minimum number of iterations for FSA process.

5.3 Multiple Collision Recovery System

To simplify the analysis, previous sections considered systems with equal collision recovery probability coefficients regardless the number of collided tags per slot. For example, the probability to resolve two collided tags is equal to the probability to resolve three or four collided tags per slot. However, in practice the probability to recover one tag from two collided tags is more than the probability to identify single tag from three collided tags. Therefore, in this section, the collision recovery probability will be considered as a variable coefficient α_i, where i is the number of collided tags per slot.

In this section, a new reading efficiency metric called Multiple Collision Recovery Coefficients Reading Efficiency η_{MCRC} is proposed. The proposed efficiency includes a unique collision resolving coefficient for each number of collided tags. Hence, a novel closed form solution for the optimum FSA frame

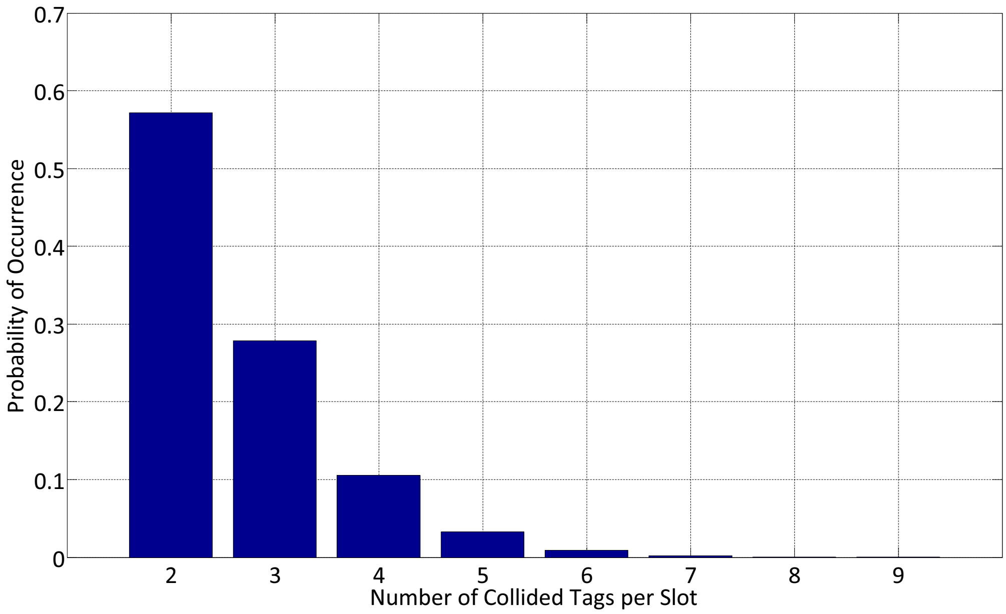


Figure 5.9: Distribution of collision probability for a collided slot in FSA, under condition of $\frac{n}{2} \leq L \leq 2n$

frame length L_{MCRC} under multiple collision recovery coefficients environment. L_{MCRC} can be optimized by finding the value of L which maximizes η_{MCRC}. According to [94], if $L \gg 1$, and $n \gg i$, we can assume a Poisson distribution:

$$P(i) \simeq \frac{1}{i!} \cdot \beta^{-i} \cdot e^{-\frac{1}{\beta}}, \tag{5.39}$$

where $\beta = \frac{L}{n}$. After substituting (5.39) in (5.38) we get:

$$\eta_{MCRC} = e^{-\frac{1}{\beta}} \cdot \left(\beta^{-1} + \frac{\alpha_2}{2}\beta^{-2} + \frac{\alpha_3}{6}\beta^{-3} + \frac{\alpha_4}{24}\beta^{-4} \right). \tag{5.40}$$

Now we have to find the value of β which maximizes η_{MCRC}. This is achieved by differentiating the reading efficiency in (5.40) with respect to β and equate the result to zero. After differentiating, the equation can be simplified as:

$$\begin{aligned} -e^{-\frac{1}{\beta}} \cdot \Bigg(\beta^{-2} + \beta^{-3}(\alpha_2 - 1) + \frac{\beta^{-4}}{2}(\alpha_3 - \alpha_2) + \frac{\beta^{-5}}{6}(\alpha_4 - \alpha 3) \\ - \frac{\beta^{-6}.\alpha_4}{24} \Bigg) = 0. \end{aligned} \tag{5.41}$$

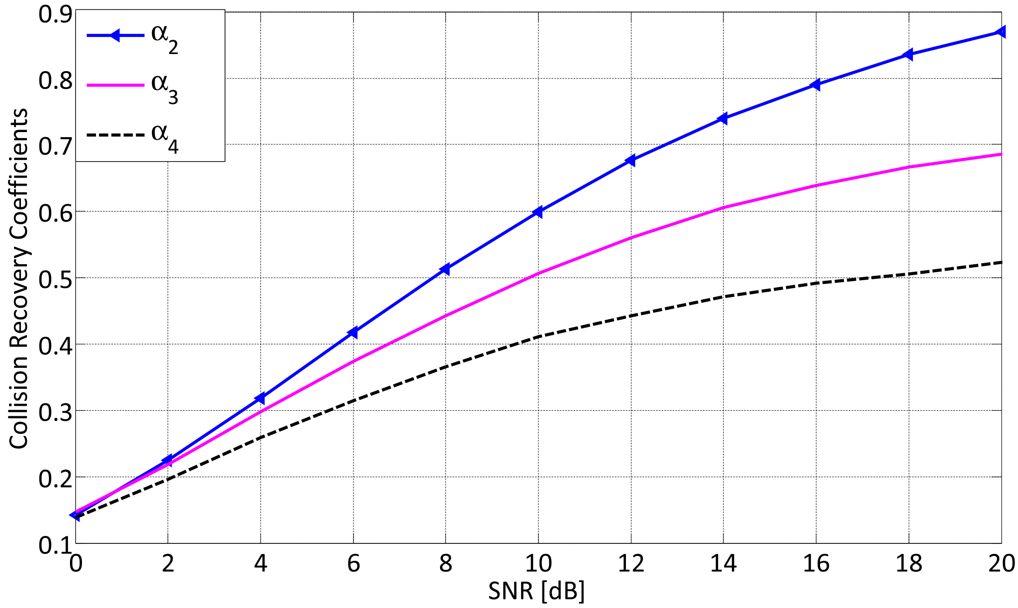


Figure 5.10: Simulation results for the average collision recovery coefficients versus SNR using the strongest tag reply receiver. α_2, α_3, and α_4 are respectively the collision recovery probability or two, three, and four collided tags per slot.

which matches the results in [59].

5.3.2 Collision Recovery Coefficients Calculations

Now the calculation of the collision recovery coefficients α_2, α_3 and α_4 will be clarified, which are the main optimization variables in our proposal. The values of these coefficients are strongly dependent on the receiver type. Calculations of the collision recovery coefficients are done based on an RFID reader model that utilizes the capture effect. The reader resolves the collision based on the strongest tag reply. Therefore, the collision can be resolved with a certain probability, if the strongest tag reply is stronger than the summation of the other collided tags at the same slot.

The main advantage of this reader is that it does not need any channel state information (CSI) to recover the strongest tag. According to EPCglobal C1G2 standard [11], collisions in RFID systems occur only within the 16 bits packet called $RN16$. If any single bit error occurs in this packet, the total packet

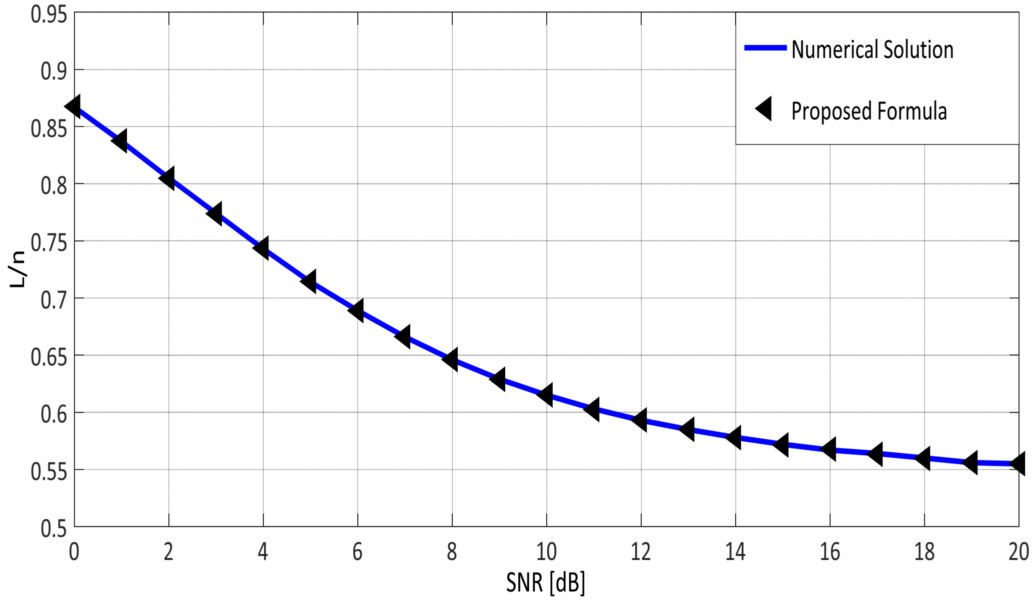


Figure 5.11: Frame length comparison between the proposed formula in (5.44) and the numerical solution for different SNR values.

has to be considered lost. Therefore, the meaning of the collision recovery probability coefficients α_i is the probability that the RFID reader can identify a complete $RN16$ packet from i collided tags. Therefore, the collision recovery coefficient can be expressed as $\alpha_i = (1 - PER_i)$, where PER_i is the Packet Error Rate for i collided tags. In this work, we measure the SNR for each slot, then we calculate the average SNR per frame as $E\left\{\frac{|h|^2 \cdot x^2}{\sigma^2}\right\}$, where σ is the standard deviation of the Additive White Gaussian Noise (AWGN) per slot, and at last, we used normalized signal power, i.e. $E\{x^2\} = 1$. Based on [81], we assumed that the equivalent channel coefficients h follow Rayleigh fading. The channel coefficients are independent zero mean circularly symmetric complex Gaussian random variables with normalized energy $E\left\{|h|^2\right\} = 1$, and all tags are statistically identical, which means all of them experience the same average path loss. Therefore, the average SNR per frame is $E\left\{\frac{1}{\sigma^2}\right\}$.

Figure 5.10 shows the values of the collision recovery coefficients versus the average SNR per frame using the strongest tag reply receiver. In these simulations, a sampling frequency of $f_s = 8\,\text{MHz}$ is used, and the tags used FM0 as an encoding scheme. Finally, to clarify the worst case effect of the collision recovery coefficients, we used the highest symbol rate BLF $= 640\,\text{kHz}$.

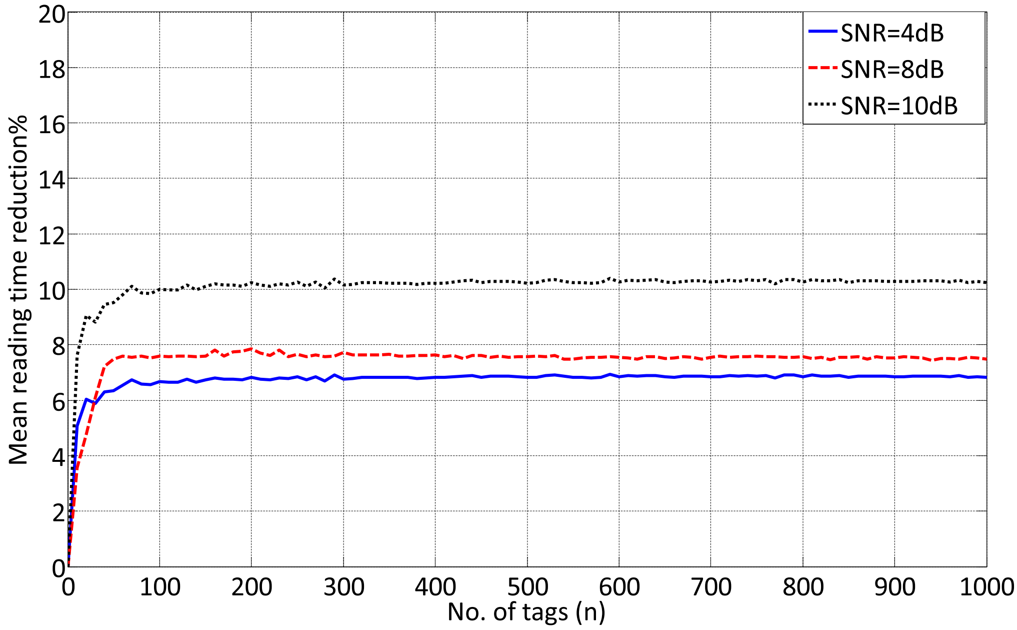


Figure 5.12: Mean reading time reduction using the proposed MCR compared to the conventional frame length $L = n$ for perfect number of tags estimation using $C_t = 0.2$ and different SNR values

5.3.3 Closed Form Solution vs. Numerical Solution

For each RFID reader, each SNR leads to corresponding values for the collision recovery coefficients α_2, α_3 and α_4. Figure 5.11 shows a comparison between the proposed formula (5.44) and the numerical solution which maximizes the reading efficiency in (5.40) versus the SNR. Both simulations used the same receiver model, which is the strongest tag reply receiver. According to figure 5.11, the proposed formula gives identical results compared to the numerical solution at the complete SNR range.

5.3.4 Mean Reading Time Reduction

The total average number of slots needed to identify a complete bunch of tags is calculated using the strongest tag reply receiver in [57]. FSA with initial frame length $L_{ini.} = 16$ is used as an anti-collision algorithm. Figure 5.12 illustrates a comparison between the percentages of saving time using the proposed MCR and the conventional frame length $L = n$ assuming perfect number of tags

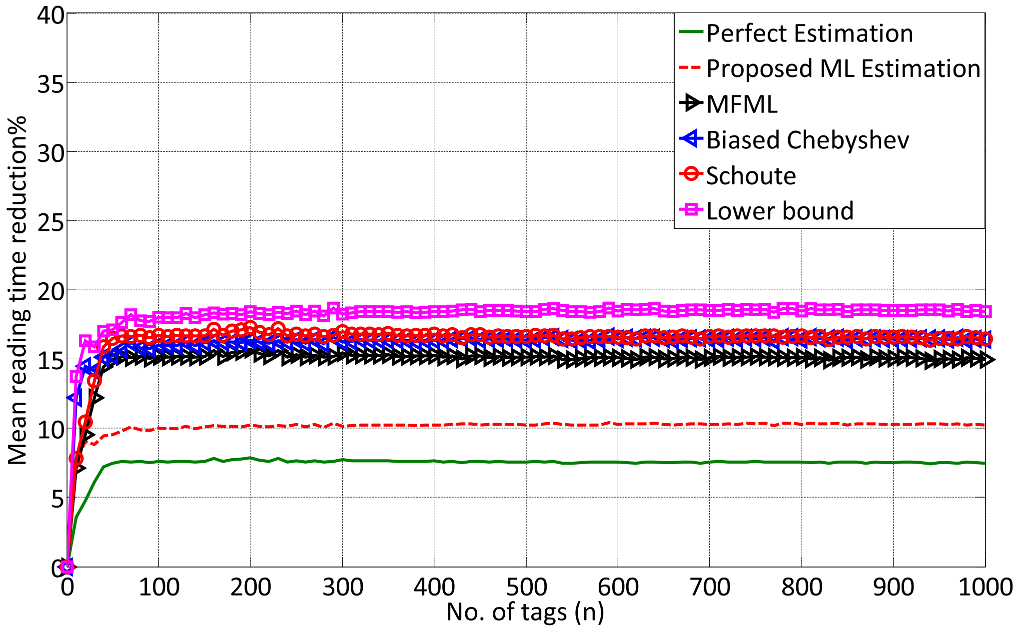
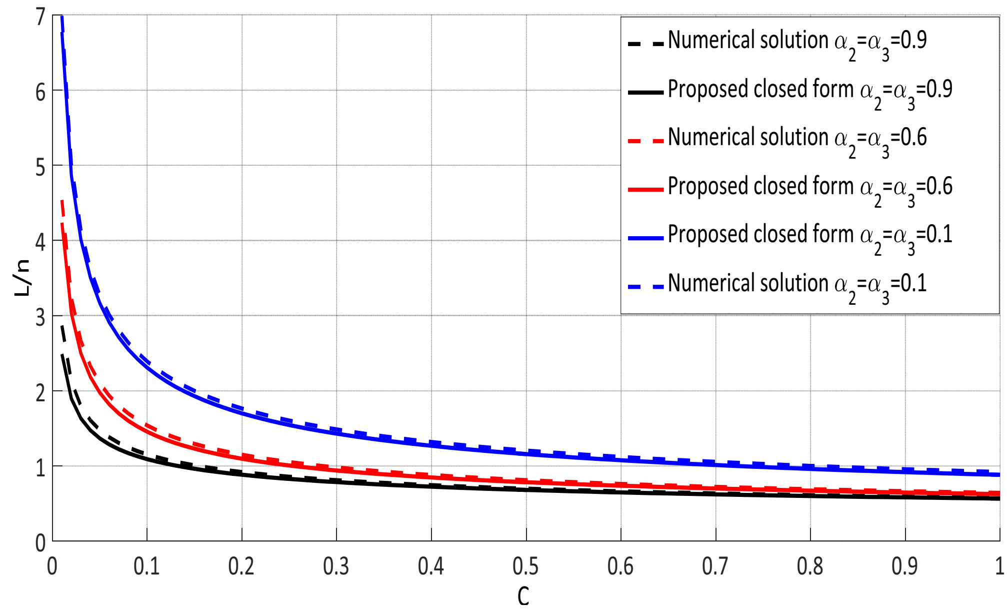


Figure 5.13: Mean reading time reduction using the proposed MCRA compared to the conventional frame length $L = n$ using different anti-collision algorithms with $C_t = 0.2$ and $SNR = 4\,\text{dB}$

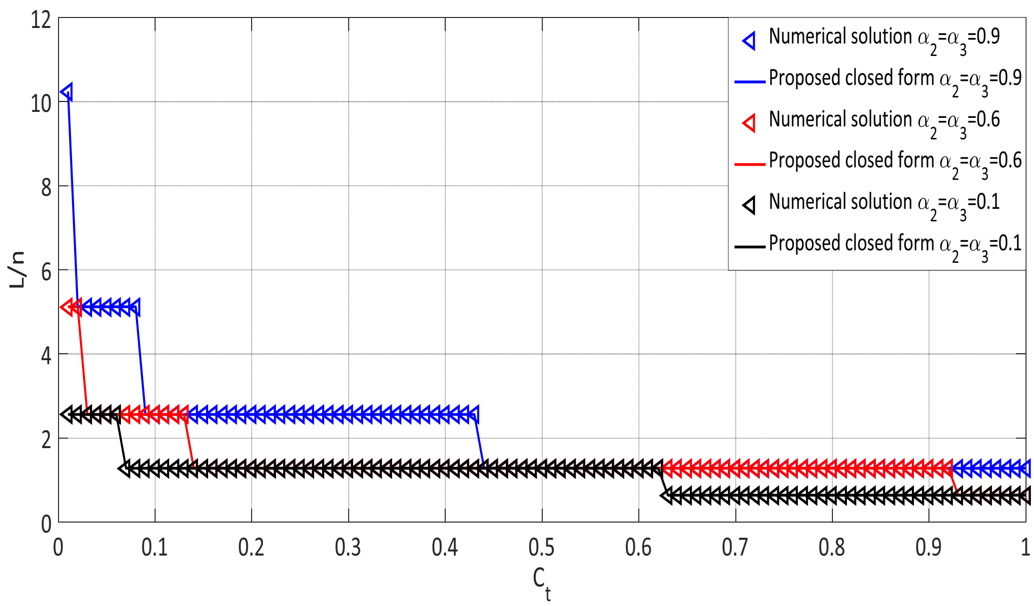
estimation. The simulation uses $C_t = 0.2$ and different SNR values. According to figure 5.12, when the value of the SNR increases, the collision recovery probability increases. Hence, the mean reading time reduction also increases.

Figure 5.13 shows the percentages of saving time with the proposed MCR compared to the conventional frame length $L = n$ using different anti-collision algorithms with $C_t = 0.2$ and $SNR = 4\,\text{dB}$.

In this section, the FSA reading efficiency is proposed for equal slot duration system with multiple collision recovery coefficients. However, practically, there are differences in the slot durations depending on the slot type. Therefore, in the following section, the FSA reading efficiency will consider the differences in slot durations as well as the differences in the collision recovery coefficients.



(a) Non-quantized Frame length



(b) Quantized Frame Length

Figure 5.14: Frame length comparison between the proposed formula and the numerical solution versus the SNR using the strongest tag reply receiver.

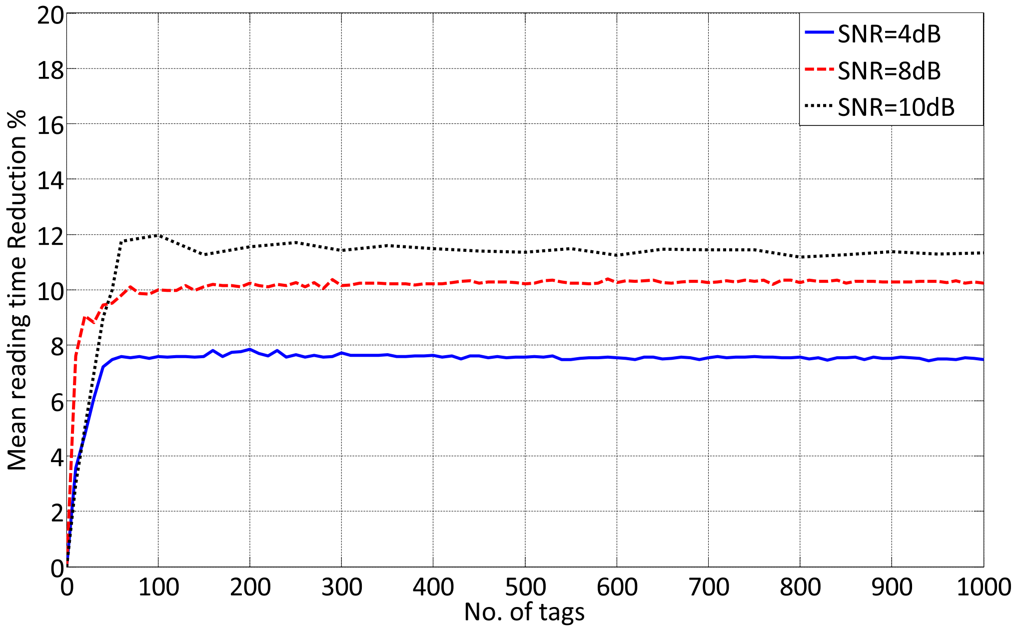


Figure 5.15: Mean reading time reduction using the proposed TMCRA compared to the conventional frame length $L = n$ for perfect number of tags estimation using $C_t = 0.2$

5.4.3 Mean Reading Time Reduction

Figure 5.15 presents the saved time using the proposed TMCRA compared to the conventional frame length $L = n$ for perfect number of tags estimation. The simulation results are based on the slot duration constant $C_t = 0.2$, as it is considered as a practical value used in the EPCglobal class 1 gen 2 standards [11] and different values of SNR, as each SNR leads to corresponding values for the collision recovery coefficients α_2, α_3 and α_4. According to figure 5.15, when the value of the SNR increases, the collision recovery probability increases. Hence, the mean reduction in reading time also increases.

Figure 5.16 shows the percentages of saving time using the proposed TMCRA compared to the conventional frame length $L = n$ using different anti-collision algorithms with $C_t = 0.2$ and strongest tag reply receiver with average $SNR = 8\,\text{dB}$ which is corresponding to $\alpha_2 = 0.52$, $\alpha_3 = 0.45$ and $\alpha_4 = 0.35$. According to figure 5.16, the mean reading reduction in reading time for different estimation algorithms is between 10% and 18%. FSA with perfect number of tags estimation algorithm leads to less number of iterations in the reading

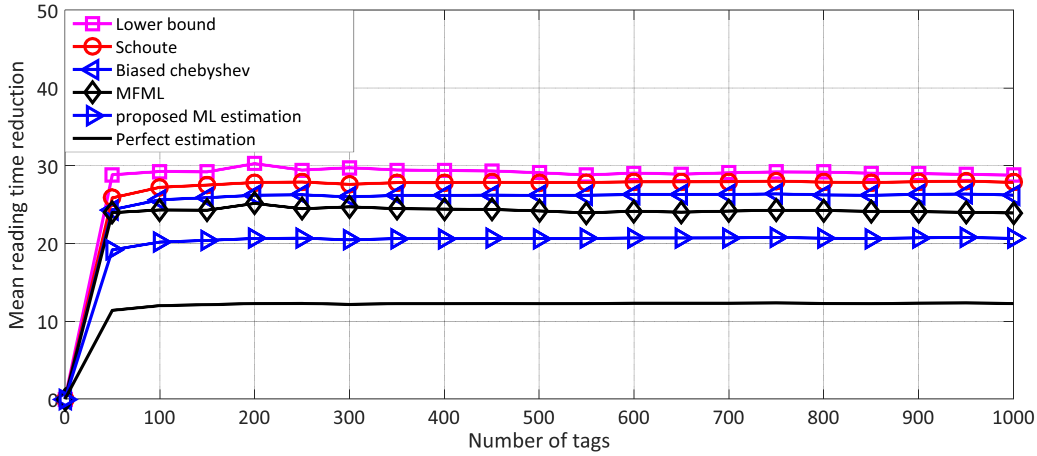


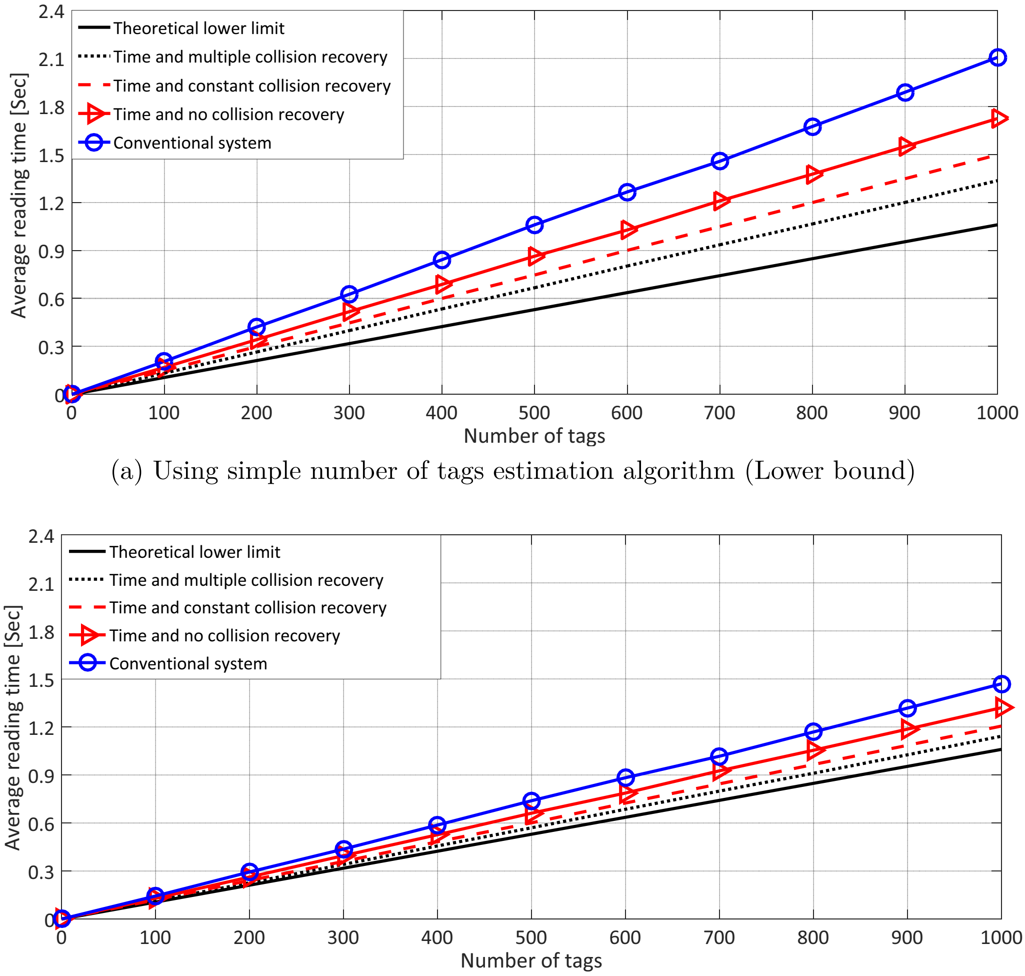
Figure 5.16: Mean reading time reduction using the proposed TMCRA compared to the conventional frame length $L = n$ using different anti-collision algorithms with $C_t = 0.2$ and $SNR = 10\,\text{dB}$

process. Thus it results the lower bound of the mean reduction in reading time. On the other hand, FSA with simple estimation algorithm e.g. Lower bound leads to more number of iteration and higher percentage of saving time.

5.5 Comparison of the Proposed Algorithms

The most crucial performance metric in RFID systems is the average total reading time for an existing number of tags in the reading area. This section will summarize the performance of the DFSA with the proposed frame lengths. It compares between the average total reading time of the proposed frame lengths and the conventional one which assumes that $L_{opt} = n$. Furthermore, it illustrates how far are the proposed systems compared to the theoretical lower limit of the EPCglobal C1 G2 standard [11], which gives the minimum identification time for UHF RFID system. The theoretical lower limit is achieved when the system identifies a single tag per slot. Therefore, the minimum number of slots to identify n tags is n successful slots.

Figure 5.17 shows the simulation results of the average reading time for DFSA using the following parameters: Slots duration constant $C_t = 0.2$, with $te = 60\,\mu\text{s}$, $tc = 360\,\mu\text{s}$, and $ts = 1060\,\mu\text{s}$, which are the practical values from real measurements using a Universal Software Defined Radio Peripheral (USRP



(a) Using simple number of tags estimation algorithm (Lower bound)

(b) Using the proposed collision recovery aware ML number of tags estimation algorithm

Figure 5.17: Average reading time of the proposed systems, conventional FSA and the theoretical limit

B210) [63]. Strongest tag reply receiver is used with average $SNR = 10\,\text{dB}$, which leads to the following collision recovery coefficients, $\alpha_2 = 0.6$, $\alpha_3 = 0.5$, $\alpha_4 = 0.4$.

Figure 5.17a shows the average reading time for DFSA using lower bound number of tags estimation algorithm. The main objective of theses simulations is to evaluate the performance of the proposed frame lengths formulas without the effect of the proposed ML number of tags estimation algorithm. As discussed in chapter 4, the lower bound number of tags estimation neglects the collision recovery capability of the physical layer and gives the minimum num-

Table 5.2: Performance analysis for the proposed frame length formulas

(a) Average reading time reduction using the proposed frame length formulas compared to the conventional DFSA $L = n$

	Simple estimation algorithm (LB)	Proposed ML estimation
Time and no CR	16 %	10 %
Time and constant CR	25 %	18 %
Time and multiple CR	30 %	22 %

(b) Average remaining room of improvement for the proposed frame length formulas to reach the theoretical lower limit of EPCglobal C1 G2

	Simple estimation algorithm (LB)	Proposed ML estimation
Time and no CR	35 %	20 %
Time and constant CR	25 %	15 %
Time and multiple CR	15 %	10 %

According to the above results, there is still $\approx$ 10 % can be improved between the proposed systems and the theoretical limit of the EPCglobal C1 G2 standard [11]. The main reason of this is, the allowed optimization was only in the reader side. To follow the EPCglobal C1 G2 standard [11], the tags could not be modified. Thus in the next chapter, backwards compatible improvement of the EPCglobal Class 1 Gen 2 standard will be proposed. This proposed system is compatible with the EPCglobal C1 G2 standards, i.e. the proposed tags could be jointly operated with conventional tags and identified by conventional readers without affecting the performance. Additionally, conventional tags can also be operated together with the proposed tags and can be identified by the proposed reader.