Efficient and Anonymous RFID Tag Counting and Estimation using Modulation Silencing

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***Abstract*—In RFID based inventory systems, counting and estimating the number of the surrounding tags without reading each tag individually is a challenge. In this paper we propose an estimation function that considers the variance of collision and empty slots during the estimation frame. In addition, two schemes, Variance and Modulation Silencing based Estimation (VMSE) and Modulation silencing count (MSC), are proposed to utilize the accuracy of the estimation function and modulation silencing mechanism [1] in counting and estimating the number of RFID tags. In the proposed schemes, tags participating in collision and success slots are silenced to accelerate the counting process. Requiring only minimal modification to the reader-to-tag communication procedure, the proposed schemes achieve a significant performance gain when compared to existing counting protocols in the literature.**

I. INTRODUCTION

RFID technologies provide low cost and non-line of sight data collection that enable several automatic inventory applications [2]. In a typical RFID inventory system, the different objects are tagged with RFID transponders which hold unique identifiers to be collected by the RFID readers. In some applications, the exact count of the objects, or even an estimate, might be of interest. For example, a factory manager is more likely to be interested in the number of objects produced instead of their type. Similarly, proper tag population estimation is used to facilitate faster identification process in EPC and ISO standards.

Reliable and time-efficient counting mechanisms are necessary especially when mobile objects are of concern. For example, moving containers on a conveyor belt require an efficient counting (or estimation) mechanism to capture all tags promptly while the containers are within the reader zone. However, reading the full reply (e.g., the 154 bits in EPC C1G2 standard [3]) of every tag prolongs the counting and estimation process and some tags may enter and exit the reading zone not being counted. Furthermore, revealing the whole IDs in the counting process will expose the systems to several compromising attacks (e.g., eavesdropping and tracking attacks).

Despite their efficiency in estimating the surrounding tags, the recently proposed schemes time efficiency is hindered by the lengthy time of single and collision slots especially when high accuracy is required. To overcome this, some schemes proposed a customized tag messages with either a fewer payload bits [4] or a specific data patterns [5]. However, those techniques are based on customized tag-to-reader procedures which deviated from the standard and practical implementation.

In this paper, we propose two efficient schemes utilizing Modulation Silencing Mechanism (MSM) [1] to accelerate tag counting and estimation. Modulation silencing will be used to significantly shorten both the single and collision slots time. The estimation scheme, Variance and Modualtion Silencing based Estimations (VMSE), exploits the statistics (collision, single and empty) of a small number of slots to estimate the tags population. The counting scheme, modulation silencing count (MSC), on the other hand, is based on Tree Slotted ALOHA (TSA) and dynamic framed slotted ALOHA (DFSA) with proper ending of all slots using modulation silencing. With minimal modification to the reader-to-tag communication procedures, the proposed schemes achieve a significant performance increase when compared to other schemes in the literature.

The rest of this paper is organized as follows. In Sections II and III we discuss the related work and introduce modulation silencing mechanism. In Section IV, our estimation function is proposed and in Section V the modification on MSM to accomodate prompt counting is detailed. In Section VI our estimation and counting schems are presented followed by the evaluation of their time efficeny in Section VII. In Section VIII the paper is concluded and the future extensions are discussed.

II. RELATED WORK

Recently, a number of techniques have been proposed for anonymous tag population counting and estimation [4]–[6]. A probabilistic analytical model for anonymously estimating tag population is proposed in [6]. Framed-Slotted ALOHA protocol is used to observe the number of empty and collision slots to count tags. However, the drawbacks of the estimator is the assumption of having a readable tags by the reader in a

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single round, in addition, the estimator is sensitive when the frame is relatively small compared to the tag population. Due to these constraints, an Enhanced Zero-Based (EZB) estimator is presented in [4]. By tuning the parameters for multiple iterations, the number of tags can be estimated with higher accuracy. Unlike EZB, First Non-Empty slots Based (FNEB) estimation [5] provide a key improvement by not scan the entire frame, which increases the time efficiency. However, FNEB depends on one statistical aspect of the frame (empty slots only) and did not exploit the single and collision data that present valuable information in estimating the surrounding tags.

III. PRILIMINARIES

1) Anti-collision protocols: In RFID systems, tags lack intercommunication capabilities. Hence, in the collection of the IDs of a large population of tags, the reader is responsible for organizing the replies of the tags through what is known as an anti-collision protocol. In such protocols, the time is divided into slots and the tags addressed by the reader command will send its data in that slot. Some commands may address more than one tag; hence, multiple replies are detected at the reader's antenna causing what is known as collision slots. In addition, if the commands do not address any tag, an empty slot is experienced. Ending empty slots was employed in several protocols [7] and standards [3]. However, early ending of collision slots was problematic since the tags can not respond to any reader's commands while replying back its data. A modulation silencing mechanism [1] was recently proposed to enhance the time and power efficiency of anti-collision protocols by reducing the time waste on collision and empty slots.

2) Modulation Silencing: In Modulation Silencing Mechanism (MSM), the reader informs the tags of a collision by cutting off its continuous wave (CW) transmission. The tags detect this cut-off and stop the backscattering of their data. The readers employ a Rapid Collision Detection (RCD) algorithm, while the MSM-enabled tags sense the reader signal availability by the Continuous Wave Absence Detection (CWAD) circuitry. After the CW cutoff, CWAD circuitry interrupts the tags reply by asserting Backscattering Termination and NACK (BTN) signal.

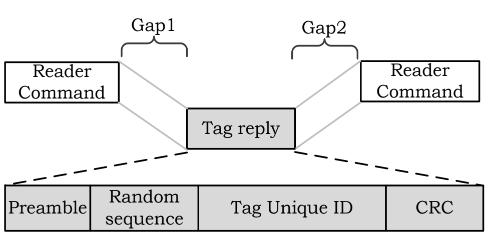

Fig. 1. Reader to Tag communication timing model

The timing model of data transmission between the tag and the reader in time slotted RFID systems is shown in Fig. 1. In MSM, if there is no tag replying to the reader command, the reader ends the slots after Gap1. If there is a single tag replying to the reader command, the reader keeps sending the CW and receiving the tag's reply. If more than one tag reply within the same slot, the reader detects a violation (i.e., not decoded as 0 or 1) in the received bits and stops its continuous wave transmission. The time periods of empty (T_e), collision (T_c), and single (T_s) slots in MSM are shown in Fig. 2.

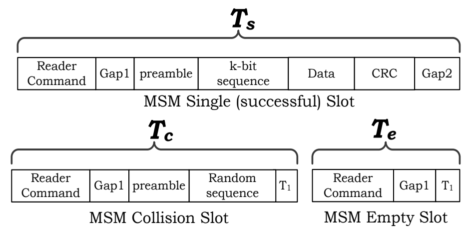

Fig. 2. Time slots in MSM, collision and empty slots are much shorter than single reply slot

IV. PROPOSED ESTIMATION FUNCTION

In this section, we describe our novel RFID tag estimating scheme, variance to mean based estimator (VMRE). The estimation algorithm is based on frame slotted ALOHA protocol in which the reader sends the number of slots (N) at the beginning of the estimation process. Every tag randomly selects a replying slot within the given frame. The reader is able to distinguish the status of each slot as either collision, single, or empty as will be detailed in Section V. In addition, the reader is assumed to be capable of ending the frame after N_E slots, where $N_E<N$ (i.e. before reading all the N slots).

After ending the estimation frame, the reader will have statistical information that infers the estimated number of surrounding tags $\hat{n}$. In our estimation functions, the observed collision (R_c), single (R_s), and empty (R_e) slots are the main indicators of the estimated tag population $\hat{n}$. However, since the size of the frame is not fixed in all applications, the relation between the collision to single slots ratio k_c and empty to single slots ratio k_e, and the estimated population need to be defined. Therefore, a lookup table (LUT) is created to map the *mean* collision to single slots ratio, $\bar{k_c}$, and *mean* empty to single slots ratio, $\bar{k_e}$, to their associated population to frame size ratio n/N (ψ).

Since the tags randomly selecting the replying slots, the average number of replying tags per slot follows a binomial distribution.The expected number of slots that have x replies is given by

$$\mu_x = N\binom{n}{x}\left(\frac{1}{N}\right)^x\left(1-\frac{1}{N}\right)^{n-x}. \quad (1)$$

Therefore, mean values of empty, single, and collision slots are:

$$\mu_e = N\left(1-\frac{1}{N}\right)^n \approx Ne^{-\psi}, \quad (2)$$

$$\mu_s = N\left(1-\frac{1}{N}\right)^n - 1 \approx ne^{-\psi} \quad (3)$$

TABLE I
LOOKUP TABLE FROM $\bar{k_c}$ $\bar{k_e}$ TO THE CORRESPONDING ψ

ψ=(n/N)	0.1	0.11	0.12	..	9.98	9.99	10
	⇑	⇑	⇑	⇑	⇑	⇑	⇑
$\bar{k_c}$=μ_c/μ_s	0.046	0.051	0.057	...	2153	2176	2200
$\bar{k_e}$=μ_e/μ_s	11.1	9.98	9.08	...	0.1002	0.1001	0.1

and

$$\mu_c = N - \mu_e - \mu_s \approx N\left(1 - (1+\psi)\, e^{-\psi}\right), \quad (4)$$

respectively.

Since the mean values are given by eq. (2),(3) and (4), a lookup table (LUT) is constructed at the reader to match $\bar{k_c}$ = μ_c/μ_s and $\bar{k_e}$=μ_e/μ_s to ψ, for ψ range from 0.1 to 10. Therefore, the table will map the averages from relatively small tag population (compared to frame size) to a very large tag populations (10 times the frame size) as shown in Table I.

After calculating k_c from the observed R_c and R_s; k_c is compared to all $\bar{k_c}$ values in the LUT. The closest value in $\bar{k_c}$ row to k_c will be mapped to the estimated ψ an dnotes as ψ_c. The same procedure will be executed to find the estimated ψ from empty slots ψ_e. However, the number of collision and empty slots is probabilistic and may deviate from the mean values $\bar{k_c}$ and $\bar{k_e}$. Hence, k_c and k_e ratios will be mapped to ψ_c and ψ_e, which are not necessarily the same. Therefore, for proper estimation of the tag population, the variance functions of both collision and empty slots are required to select the proper ψ from k_c or k_e that have a lower variance. The variance for empty slots is derived by [6] as

$$\sigma_e^2 = Ne^{-\psi}\left(1 - (1+\psi)\, e^{-\psi}\right), \quad (5)$$

and the variance of collision is defined in [4] as

$$\sigma_c^2 = Ne^{-\psi}\left((1+\psi) - \left(1 + 2\psi + \psi^2 + \psi^3\right) e^{-\psi}\right). \quad (6)$$

By plotting the two variance functions in Fig. 3, we note that the empty slots variance peaks around ψ of 1.23, collision slots variance, on the other hand, peaks at ψ =2.44. Those peak values are useful if the number of collisions and empty slots are constant with ψ. However, the collision slots number is negligible for small ψ and dominating the frame slots when ψ is more than 3. Therefore, higher variance values will not necessarily indicate higher error in estimation. Our algorithm takes the variance significance in consideration instead of the variance value and defines variance to mean ratios to select ψ that reflect more accuracy in the estimation. Variance to mean ratios (VMR) for empty and collision slots are given by

$$VMR_e = \frac{\sigma_e^2}{\mu_e}, \quad (7)$$

and

$$VMR_c = \frac{\sigma_c^2}{\mu_c}, \quad (8)$$

respectively.

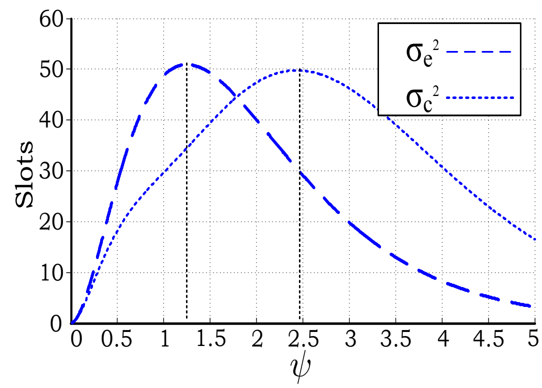

Fig. 3. Variance plot for collision and empty slots in a known frame size N

In Fig. 4 we note that the collision variance is almost the same order of the mean collision slots when ψ is small (σ_c^2/μ_c $\approx$ 1) and monotonically decreasing with the increasing ψ and the opposite is found for empty slots VMR. The two VMR curves intersect around ψ of 0.926. Therefore, ψ of 0.926 will be the threshold "T" of our algorithm that defines the selection of the most accurate estimations.

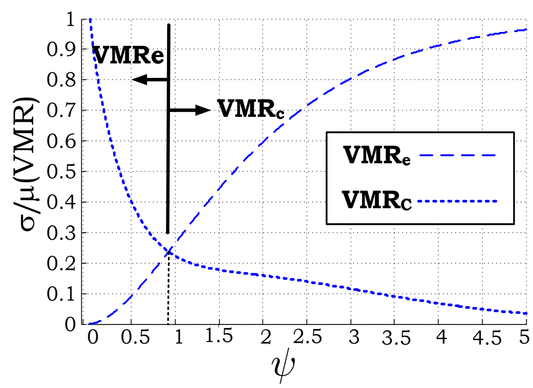

Fig. 4. Variance to mean ratio (VMR) for collision and empty slots in a known frame size N

Therefore, the expected number of tags $\hat{n}$ is: $N\psi_c$ for ψ_c, ψ_e>T, $N\psi_e$ for ψ_c and ψ_e<T, $N\frac{\psi_c+\psi_e}{2}$ otherwise,

V. MODIFIED MSM

In our estimation algorithm we will modify the MSM procedure to allow fast tag estimation process. Since the data of the tag is not of interest in counting or estimation applications, MSM early ending of the tags replies is an optimal solution to save time and power in such applications without modifying the tag reply or revealing its data. In our design the modulation silencing algorithm at the reader will be modified to allow proper ending of all slots.

In MSM, the reader sends a command to initiate the slot then it starts emitting its CW to be backscattered by the addressed tag. Tag starts the reply by sending a preamble sequence (identical for all tags) followed by the tags data. A bit level synchronization between the tags is assumed; this, the reader will not detect collisions during the preamble sequence. After the preamble, the tag(s) sends a random sequence to insure collision detection if more than one tag is replying in the same slot.

In MSM, if the random sequence is error free, the reader receives the full reply of the tag and then check the CRC. In our modified MSM, If the reader receives the random sequence without collisions it stops the Continuous Wave (CW) transmission for a period of time T_1 and send ACK to the tag. T_1 is required by the tag to detect the absence of the readers CW. If the reader detects collisions during the random sequence, it discontinues CW transmission and sends NACK to the tags[1]. In case of no reply (i.e., empty slot), the reader stops its CW immediately after the first gap period (Gap1) as in Fig. 1.

In order to estimate the length of a collision slot in MSM, the average number of bits M that will be received before detecting a collision can be given by

$$M = \sum_{i=0}^{L} i \left(2^{i(1-x)} \right), \tag{9}$$

where x and L are the number of replying tags in a specific slot and the random sequence length. Therefore, for tags sending 8-bits random sequence, if two tags replied in same slot the collision will be detected after 1.96 bits. In [1] it is shown that a random sequence of 8 bits guarantees more than 98% detection of collisions. As a result, MSM time slots periods after the modifications will have the lengths illustrated in Fig. 5.

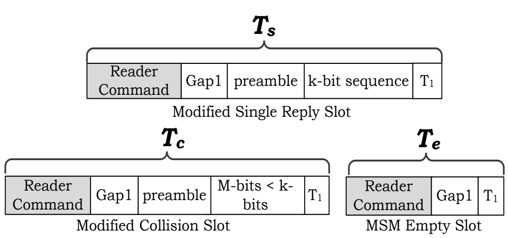

Fig. 5. Time slots in of the modified MSM, reader commad (in grey) will be needed in the counting scheme only. Note the shorter single reply slot.

VI. Estimation and counting schemes

This section will present two schemes for estimating and counting the tags anonymously using MSM.

A. Variance and Modulation Silencing based Estimation (VMSE) scheme

In our VMSE scheme we consider a set of RFID tags and a single reader. As discussed in Section IV, the cardinality estimation of the tags set is based on VMR of the collision and empty slots statistics.

[1]This applies to the counting scheme, MSC, as will be described later. In the estimation scheme, VMSE, the reader does not send ACK or NACK after T_1.

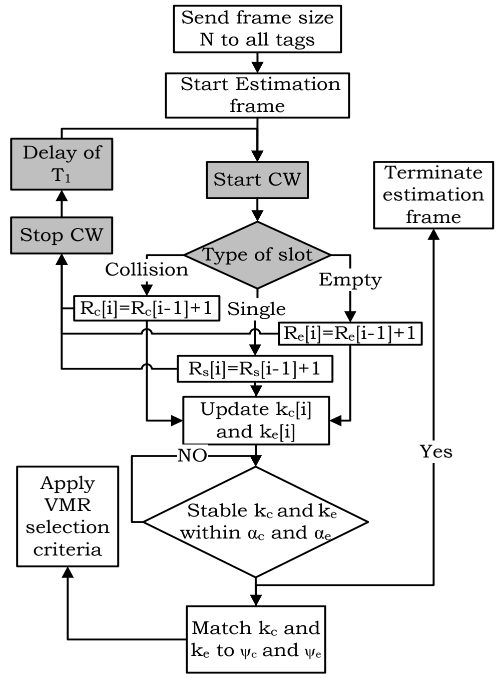

Fig. 6. The proposed VMSE scheme

VMSE is illustrated in the flowchart in Fig. 6. The reader starts the estimation round by a relatively long frame N (comparable to the frame used in generating the LUT). Within the estimation frame, the time slots are ended according to the method in Section V. For each time slot, the reader updates the values of k_c and k_e. If the average of k_c and k_e is stable within a specific predefined margin, α, the frame will be ended. Once the frame is ended, k_c and k_e are mapped to the associated ψ_c and ψ_e. Based on Fig. 4, if ψ_c and ψ_e is above the 0.926, the tags are estimated as $N{*}\psi_c$, and if the values are less than 0.926, $N{*}\psi_e$ will be the estimated population. Otherwise, the average of the mapped population will be considered.

MSM components in the flow chart are highlighted in grey. ACK and NACK are necessary if the reader want the tags to stay silent or to participate in the next frame. However, since the estimation process is based on statistics collected from a single frame, the reader will only send a command at the beginning of the frame. Consequently, if the reader detects a collision, a single reply, or no reply it will stops for T_1 then continue the CW transmission without any further commands. The tags will send their preamble and the random sequence after "Gap1 from T_1. The replies are synchronized by cutting off and resuming the CW.

In Fig. 6 VMSE is terminated when the average value of k_c and k_e, over the period of the last S slots, fall below α_c and α_e respectively. i.e., the termination criteria is met when

$$\frac{\left(\sum_{i=0}^{\frac{S}{2}} k_c[j-S+i] - \sum_{i=0}^{\frac{S}{2}} k_c[j-i] \right)}{\sum_{i=0}^{\frac{S}{2}} k_c[j-i]} \leq \alpha_c. \tag{10}$$

where *j* is the index of the current time slot. We note that lower α and higher S values will result in selecting more stable ratios for mapping in the LUT.

B. Modulation Silencing Counting (MSC) scheme

Counting can be considered as an estimation problem with 0% for error. To count the exact number of tags, an efficient identification protocol is modified for this purpose. Tree Slotted ALOHA (TSA) [8] protocol is adopted in our counting scheme with proper ending of the slots using MSM. MSC is depicted in Fig. 7 where the VMRE estimation function is employed to estimate the optimal frame sizes to the TSA.

If the resulting tag estimate by VMRE, $\hat{n}$, is higher than the maximum allowed frame size, N_{max}, then the tag population is divided into groups. Each groups will roughly contain a comparable number of tags to N_{max} to have the maximum efficiency ALOHA based protocols [1]. The number of groups dictates the last p bits in the tags ID that the tags must check to determine the group that it belong to. p can be given determined as

$$p = \lceil \log_2 \frac{\hat{n}}{N_{max}} \rceil. \tag{11}$$

For example, if the estimated tag population is 5000 tags and the N_{max} is 512 slots, the number of bits that determines the group is 4 bits. Therefore, the tags that have an ID ending 0000 it belongs to the first group of tags that will be identified using Dynamic frame slotted ALOHA. MSC utilizes modulation silencing mechanism to end the slots and acknowledge the tags participating in every slot. In VMSE, there is a single frame where the tags will not participate more than once; thus, acknowledging the replies is not needed. On the other hand, in MSC several frames are introduced for each group until the frame is collision free. Therefore, to prevent the tags with a single reply from replying in more than one frame, the single replies tags are positively acknowledged to remain silent until the counting process is concluded. Conversely, the tags involved in collision replies are negatively acknowledged in order to participate in the next frame.

VII. Performance Evaluation

In this section, we evaluate the performance of the proposed schemes in terms of accuracy and time efficiency. In [5], a comprehensive comparison is provided between different estimators that provide specific desired estimating accuracy under EPC global Class-1 Gen-2 specifications [3] . The comparison includes Combined Simple Estimator (CSE) [4], the Unified Probabilistic Estimator (UPE) [6], and the Enhanced Zero-Based (EZB) estimator [6], and FPNE estimator [5]. The provided results were given for a confidence level of 5% and averaged over 100 iterations. Similarly, we test our VMSE scheme in Matlab simulation environment over different values of α over 100 iterations.

Experiment plot for estimating tag population with α of 0.2 and 0.05 is shown in Fig. 8 and Fig. 9, respectively. The plotted results show that our estimator achieves the same accuracy

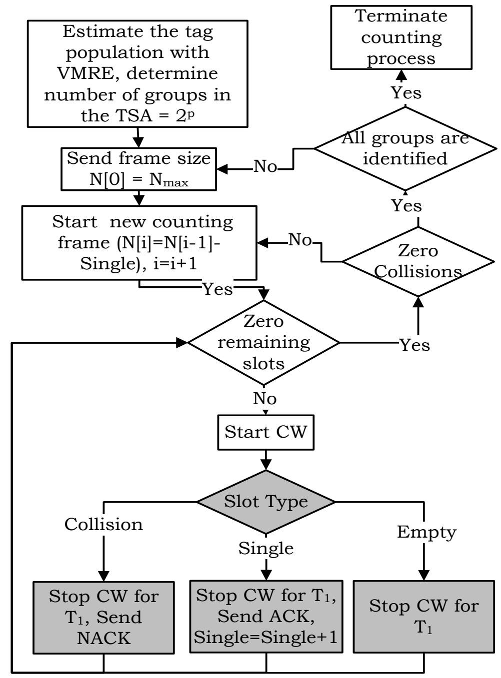

Fig. 7. The proposed countng scheme

TABLE II
SLOT COUNT TO ESTIMATE WITHIN 5% ERROR MARGIN AFTER 100 ITERATIONS

Tag population ⇒ Estimator ⇓	100	500	1000	5000
CSE	3247	3396	4005	7151
UPE	1380	2040	2130	2250
EZB	21052	21052	21052	21052
FNEB	84559	46525	26010	6510
EFNEB	5732	5758	5683	5661
Proposed Scheme	3600	3640	3710	4620

(within 5%) with much less slot count when compared to other estimators as shown in Table II. The frame size used for estimation is 512 slots, and the collision to single slots ratio, k_c, was used for estimating tag population over 500 tags and empty to single slots ratio was used for tag population under 500 tags. Despite the stability in the variance to mean value of the collision for high ψ values, the variance of the single slots will be as high as the mean value of the single slots which introduce an instability in k_c. Therefore, we note that the accuracy of estimation drop when ψ is more than 10.

A. Time efficiency

VMSE provides an accurate estimation within a small number of slots. Even though the number of slots that a reader has to send is an indicator of time efficiency, the time of each slot in different estimators vary according to the customized reader-to-tag communication model. MSM enhances the performance of our schemes by providing a significant reduction of collision, single, and empty slots based on the timing specifications of EPC Class1 Gen2 standard [3]

TABLE III
SLOTS LENGTH IN μS WITH MSM FOR COUNTING (WITH READER COMMAND) AND ESTIMATION (WITHOUT READER COMMAND)

slot type	collision	single	empty
VMSE	117.2	145.3	70
MSC	192.2	220.3	145

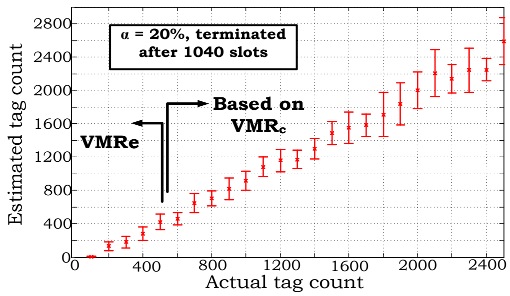

Fig. 8. The expected population after 100 iterations with an average 36 slots per iteration for α=20%

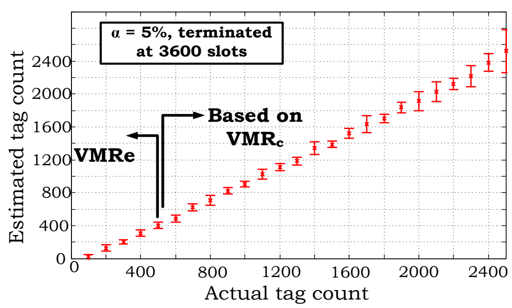

Fig. 9. The expected population after 100 iterations with an average 36 slots per iteration for α=5%

as shown in Table III.

In Fig. 10 the absolute time for estimating the tags within 5% error margin (as reported by [5]) is plotted in addition to the time for estimating the tags within 5% error margin usinng the proposed estimation scheme. The proposed scheme achieves a significant reduction in the absolute time of estimating or counting the surrounding tags.We note that the estimators will have a margin of error that will increase the number of slots. For example, if the margin of error is within 0.1% of the tag population, the number of slots will increase dramatically compared to 5% error margin. In TableIV the total time of countign several tag population is presented. we note that achieving the exact count using our scheme is even more effecient than the time of estimation within 5% in previously proposed estimators.

VIII. CONCLUSION

In this paper, we consider the problem of estimating the number of distinct tags without revealing the tags ID for densely populated RFID tags environments. A new variance to mean ratio (VMR-based) estimation function is presented that considers the variance in estimating the tag count using a pre-defined LUT. We proposed estimation and counting schemes, VMSE and MSC, based on the VMR estimation function and a modified MSM procedure. The proposed schemes combine the accuracy of VMR estimation function and the time efficiency of MSM to deliver rapid, accurate, and anonymous tag estimation and counting that outperform recent estimation schemes in the literature for a wide range of tag population.

TABLE IV
TOTAL COUNTING SLOTS AND TIME (IN μS) USING THE PROPOSED MSC WITH N_{max}=512 (α= 0.2 FOR ESTIMATION PHASE)

Tag population	100	500	1000	5000
Total counting slots	3247 228	3396 1390	4005 2780	7151 13900
Total counting time	0.51	0.73	1.02	3.19

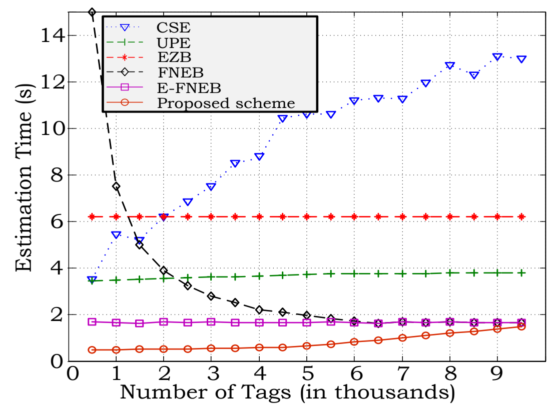

Fig. 10. Comparison from [5] in addition our proposed VMSE performance

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