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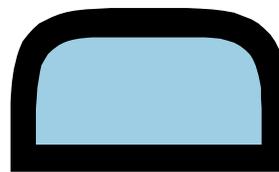
# Efficient frequency sharing of baseband and subcarrier coding UHF RFID systems

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*Report Abstract: UHF band passive RFID systems have been steadily adopted by industries leveraging the long range automatic identifications. For the applications which demand large number of readers to be located in a limited geographical area, the interference rejection among readers is important. The coding method, baseband or subcarrier coding, of the tag to reader communication link entails a significant influence onto the interference rejection. An introduction of subcarrier coding system among existing baseband coding systems need to be carefully done accordingly. This paper examines the frequency sharing of baseband and subcarrier coding UHF RFID system from the perspective of transmission delay using a numerical simulation. It is revealed that frequency band need to be divided in accordance with the coding method otherwise, a mixed operation fundamentally works against subcarrier coding system.*

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## 1. Introduction

UHF band passive RFID systems have been steadily adopted by industries leveraging the long range automatic identifications. If a large number of readers are located in a limited geographical area, it is usually referred to as a dense reader environment, in which the interference may degrade the RFID system performance [1]. If the application requirement enforces a dense reader environment [2] we need to coordinate the reader transmission and the channel allocation in order to avoid harmful interference between readers. The choice of coding method of the tag to reader (T-R) link is very much influential to the interference problem. There are two representative coding methods, the baseband coding such as FM0 in ISO/IEC18000-6 Type A and Type B and the subcarrier coding such as Miller subcarrier in ISO/IEC 18000-6 Type C. In this paper, a baseband system denotes an RFID system which uses baseband coding, while a subcarrier system denotes an RFID system which uses subcarrier coding each for T-R link.

Subcarrier coding, in which the principal tag backscatter spectrum is separated from the carrier frequency, is a powerful tool to alleviate the performance degradation stemming from the interference among passive RFID systems. The operation of multiple subcarrier systems usually does not demand strict frequency sharing technique, such as carrier sensing, to achieve high frequency efficiency. It should be noted, however, that we need to protect the inherently weak T-R link, namely the subcarrier, from other systems, such as baseband systems and other short range devices (SRD) operated in the same frequency band. The reader to tag (R-T) link of subcarrier system is so immune against the interference that the other wireless systems, such as baseband systems, cannot share the spectrum. The subcarrier systems, in principle, should be separated, in frequency spectrum wise, from baseband systems both for the sake of baseband system and subcarrier system. The frequency separation, however, results in the decrease of frequency spectrum available to baseband systems. It is important to evaluate the performance of both baseband and subcarrier systems when the two systems share the spectrum.

In this paper, we examine the influence of introducing subcarrier systems into a frequency spectrum in which a number of existing baseband systems are in operation under a carrier sensing requirement. The situation can be found in Japan and Europe where there is a movement to introduce carrier sense free channels to enhance the spectrum efficiency, technically from the subcarrier systems point of view [3]-[5]. For example, in Japan, the government and RFID proponents are discussing the elimination or significant relaxation of carrier sensing requirement in two channels out of nine channels for UHF passive RFID.

The examination, in this paper, of the co-existence of subcarrier and baseband systems is performed with an UHF RFID MAC simulator that the author's group has been developing.

In Section 2, the UHF RFID MAC simulator is introduced with experimental verification. In Section 3, the influences of frequency sharing among baseband systems and subcarrier systems is evaluated.

## 2. UHF RFID MAC simulator

### 1.1. Overview of UHF RFID MAC simulator

The MAC simulator computes the transmission availability of readers subjected to carrier sense and duty cycle requirements. The duty cycle is defined as a combination of maximum continuous transmission time (TX\_ON) and the minimum cessation time (TX\_OFF). The duty cycle in conjunction with carrier sensing (Listen Before Talk) determines the transmission availability (**Figure 1**). Three dimensional positions and orientations of the reader antennas, antenna patterns of tags and readers and the transmission spectrum mask are considered in the simulation. The air-protocol between reader and tags are not included in the MAC simulation. Transmission channels and the carrier sensing channel can be specified reader by reader.

When a reader demands to transmit, it first examines the transmission channel to see if it is occupied by other system. If the received power in the channel is below the predefined threshold value, the reader registers the channel to internal channel queue. After examining all the channels, the reader chooses the minimum power channel from the internal channel queue. By doing this, we can increase the total frequency efficiency [5].

In the simulation, a subcarrier system listens to the subcarrier channel first with predefined threshold level depending on the distance between the reader and the tag. If the received power in the subcarrier channel is less than the threshold value, the reader transmits the signal until TX\_ON is expired. If there is a harmful background noise, the subcarrier system suspends the transmission otherwise the subcarrier will be overridden by the noise. Without this receive channel carrier sensing in the simulation, the frequency sharing efficiency of the subcarrier system becomes impractically high. In the real implementation without receive channel carrier sensing, the delay is equivalent to packet losses.

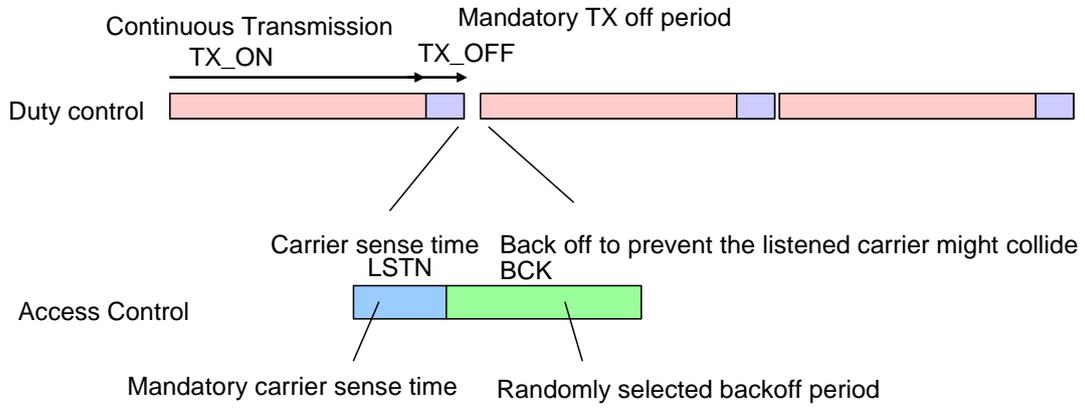
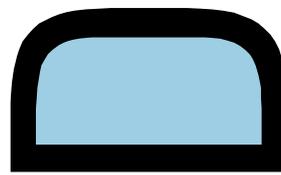


Figure 1 Duty control and carrier sensing definition

The state transition model of a reader is shown in Figure 2 .

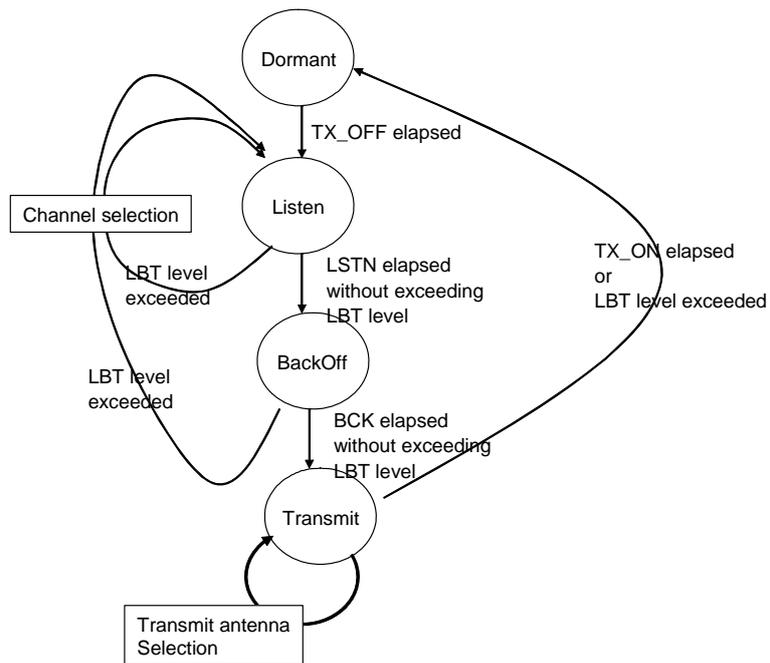


Figure 2 Reader state transition model

## 1.2. Experimental verification of UHF RFID MAC simulator<sup>1</sup>

The validity of UHF RFID MAC simulator was examined in anechoic chamber experiments. In the experiment, three baseband system, comes from different reader manufacturers, which are conformal to the type certificate requirements in Japan (**Table 1**) are used.

Table 1 Typical type certificate requirements for UHF RFID in Japan

Item	Requirements	Note
Carrier frequency (MHz)	952.2 – 953.8MHz	200kHz separation 9 channels
Maximum EIRP	36dBm	
Channel separation	Unit channel:200kHz	Channel aggregation is allowed
Frequency sharing requirement	Carrier sensing: -74dBm/channel TX_ON: 4sec TX_OFF: 50msec	A Channel denotes an unit channel or aggregated unit channels.

In the current Japan regulation environment, the number of available channels for 4W EIRP UHF RFID reader is nine, each of which is 200kHz, as shown in **Figure 3**.

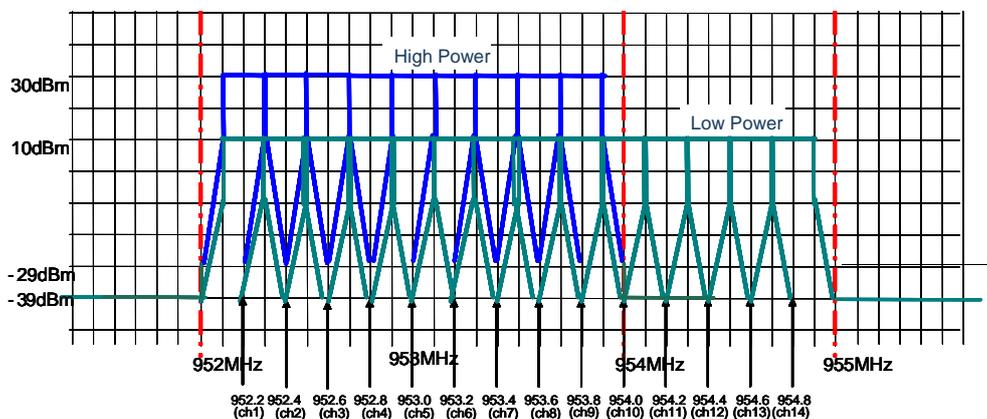


Figure 3 UHF RFID channel layout in Japan

High power represents 4W EIRP readers which is the primal interests of this white paper. Low power, on the other hands, denotes 20mW EIRP readers. The requirement on the spectrum mask of the high power reader in the vicinity of the assigned frequency band is shown in Figure 4

<sup>1</sup> This section is a part of research that Auto-ID Lab Japan had pursued in [7]

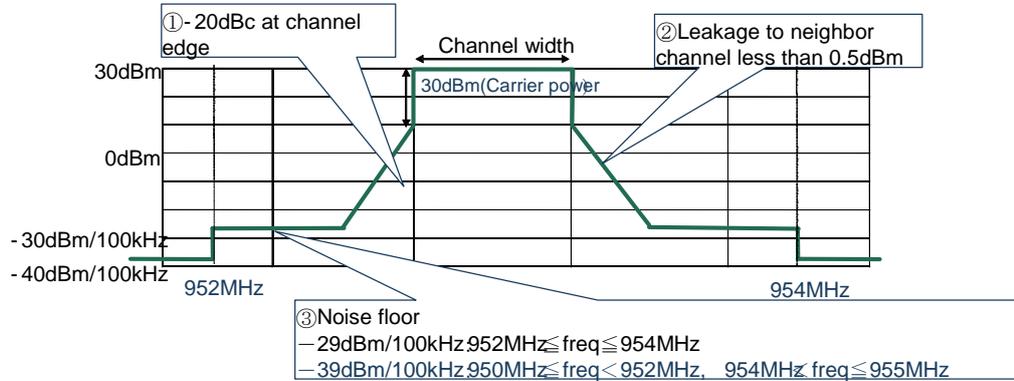
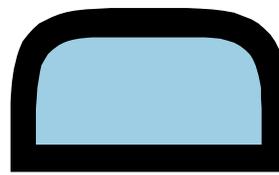


Figure 4 Spectrum mask requirement for 4W EIRP readers

The specifications of three baseband systems are listed in Table 2.

Table 2 Specifications of the baseband systems

	System A	System B	System C
R-T link bit rate	40kbps	40kbps	40kbps
T-R link bit rate	40kbps	40kbps	40kbps
T-R link coding	FM0	FM0	FM0
R-T link coding	PIE	PIE	Manchester
TX_OFF	50msec	1134msec	50msec

The three baseband systems are positioned in a triangular arrangement separated 5m each other as in Figure 5 in plane view. A photo of the anechoic chamber experiment is shown in Figure 6. Each baseband systems communicate with corresponding 20 tags. In order to determine the separation distance between tags and readers, we first measured the distance at which each readers can read at least 80% (16 tags) or above. Then the separation distance is determined by multiplying 0.70 to the distance, by which we increases the receiving power at tags by 3dB.

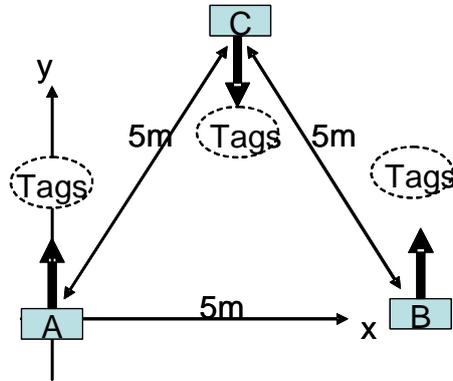
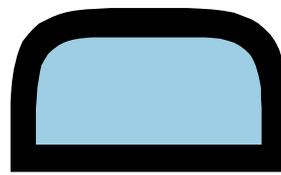


Figure 5 Readers arrangement

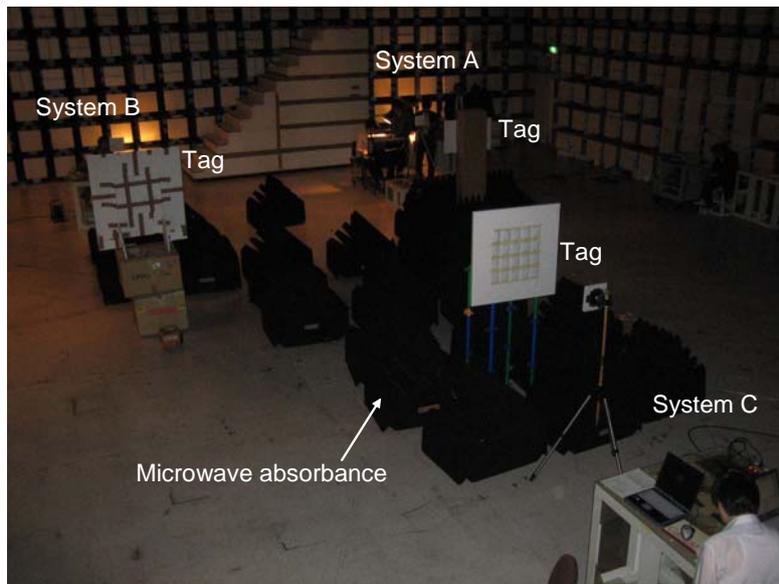


Figure 6 Position of three baseband systems.

Each reader selects a transmission channel from the predefined available channels. Five channel patterns are examined (Table 3). When multiple channels are available for a system, the system selects a vacant channel in accordance with the factory programmed algorithm.

Table 3 Channel patterns

Pattern	Available channels		
	Reader A	Reader B	Reader C
1	5	5	5
2	5	4, 5, 6	4, 5, 6
3	5	3, 5, 7	3

4	5	1、5、9	1
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We have measured the total (summed) transmission time of each reader in 60 seconds, and compared the results with that of the UHF MAC simulator. Figure 7 shows the total transmission time for channel pattern 1, in which the three readers share a single channel (channel five) to transmit. It is shown that carrier sensing provides even frequency sharing among three readers. The relative low availability of Reader B is due to the longer TX\_OFF time (see Table 2) for the post processing of the retrieved data. .

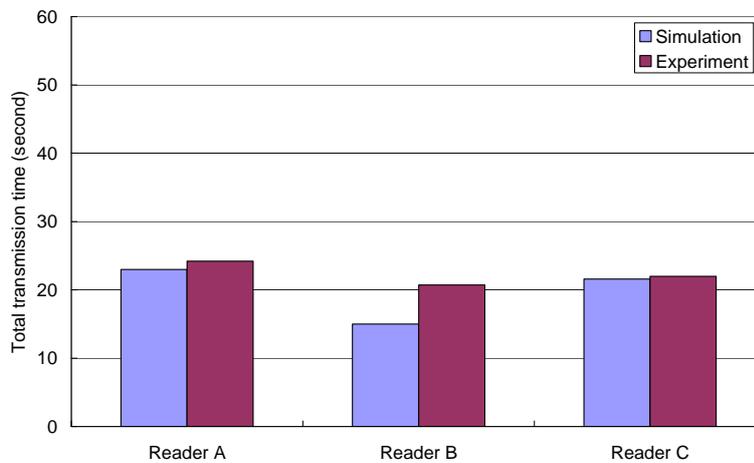


Figure 7 Total transmission time in channel pattern 1

The total transmission time in the channel pattern 2 is shown in Figure 8.

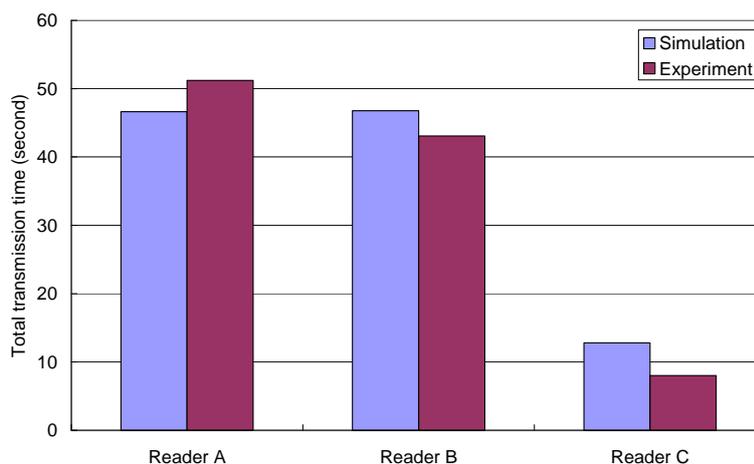


Figure 8 Total transmission time in channel pattern 2

In this channel pattern, the transmission time for Reader C is less than half of readers A and B. Since the bore-sight of the antenna of two readers, A and B, are facing to C as in Figure 6, Reader C has less chance to acquire a transmission channel due to the outband emissions of Readers A and B.

Total transmission time for channel patterns 3 and 4 are shown in Figure 9 and Figure 10, respectively.

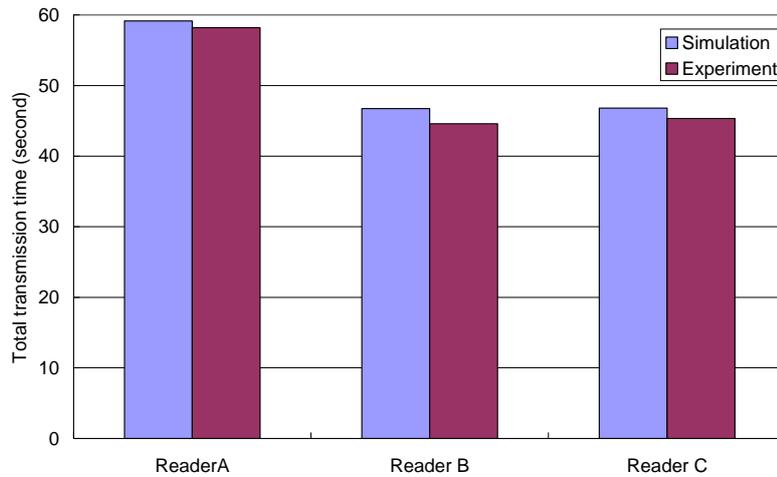


Figure 9 Total transmission time for channel pattern 3

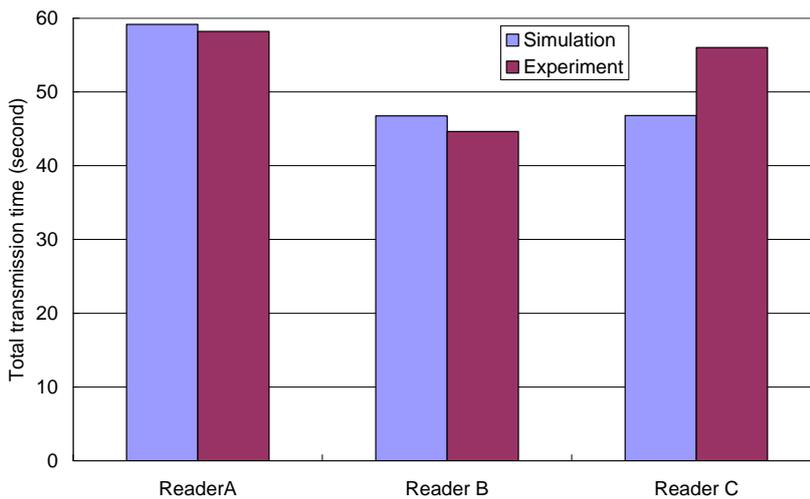
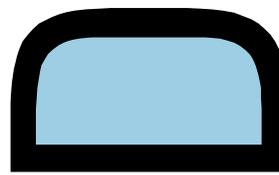


Figure 10 Total transmission time in channel pattern 4



In channel patterns 3 and 4, the three readers can transmit simultaneously because the wider channel separation mitigates the leakage of out-band-emission to the transmit channel of neighbor readers.

The average difference between simulation and measurement for the three readers are calculated by averaging the differences for all the channel patterns. The difference is approximately  $\pm 5\%$  (Figure 11). This proves that the UHF MAC simulation can predict the transmission timings with a reasonable accuracy.

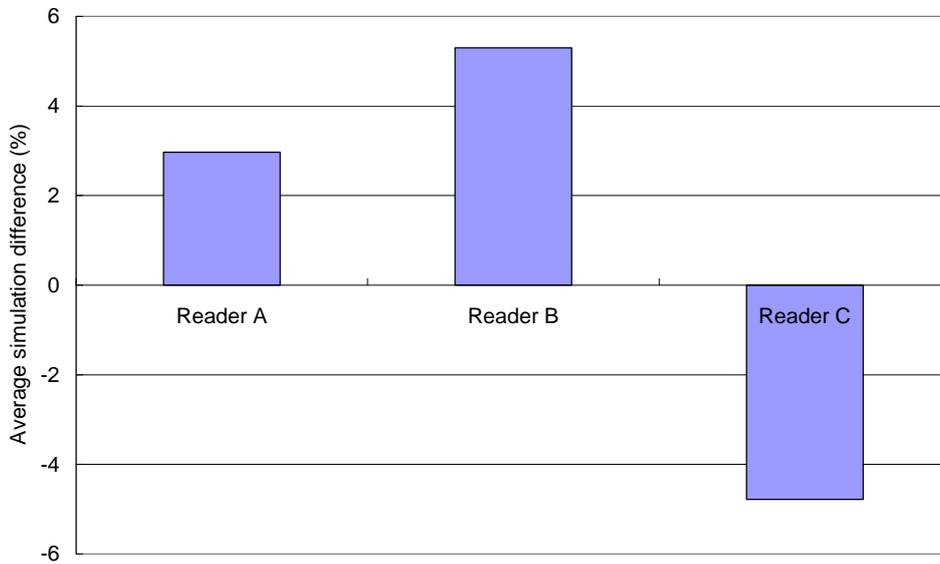


Figure 11 Simulation accuracy examination

### 3. Frequency sharing of baseband and subcarrier UHF RFID systems

In this section, we quantitatively evaluate the frequency sharing of baseband and subcarrier UHF RFID systems in Japan radio regulation environment using the UHF MAC simulator.

A mathematical model, representing twenty readers in a line arrangement is established as the input data of for the UHF MAC simulator (**Figure 12**). The model is equivalent to the model used in JAISA experiment [5], which represents one of the typical industrial installations of dense reader environment.

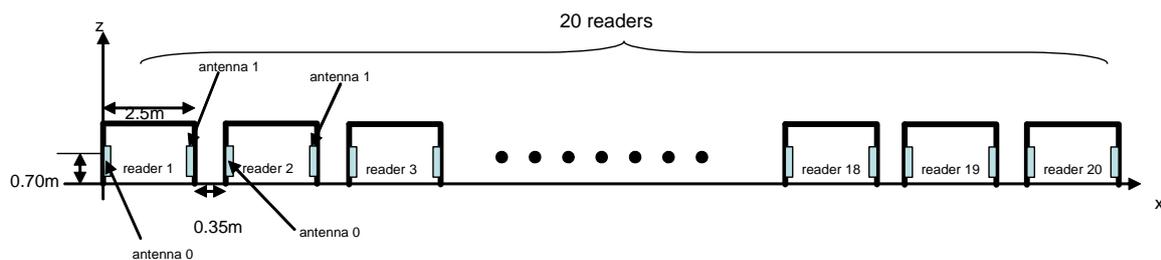


Figure 12 A dock door model comprises 20 readers

Each reader is equipped with two antennas, antenna 0 and antenna 1, for antenna diversity. Such antenna diversity is a common practice in high power RFIDs. The model involves no time gap between the antenna transitions. Each reader sends 1W power with 6dBi antenna, yielding 36dBm EIRP in one of the nine channels. The antenna pattern and the spectrum mask used in the simulations are of an existing UHF RFID reader (Figure 13 and Figure 14).

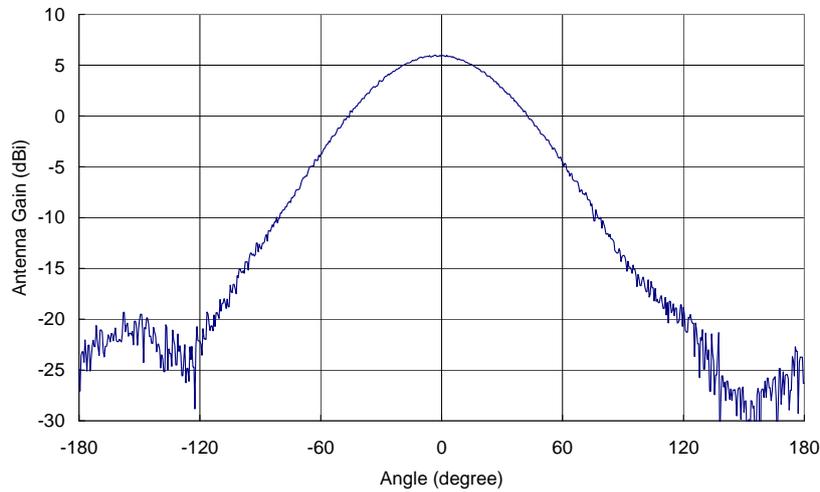
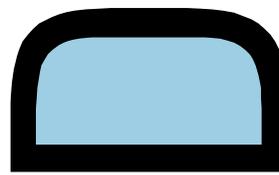


Figure 13 Antenna pattern

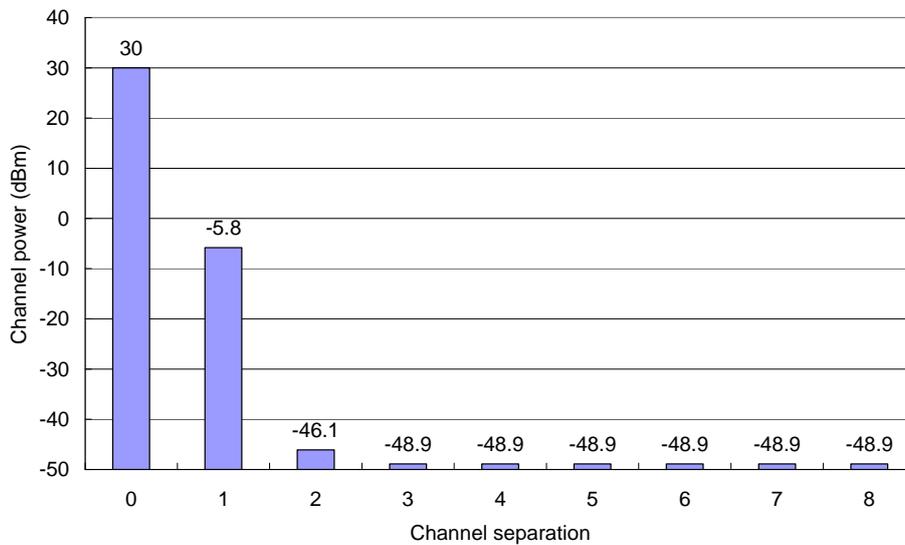


Figure 14 Spectrum mask

The continuous transmission time (TX\_ON) and cessation time after transmission (TX\_OFF) (see Figure 1) of each reader are 500msec and 50msec, respectively. Since the absolute transmission delay time depends on the continuous transmission time TX\_ON<sup>2</sup>, we have introduced a non-dimensional measure for the delay evaluation “normalized delay” which is the absolute delay time divided by the continuous transmission time (TX\_ON).

<sup>2</sup> For example, if two readers contend for one transmission channel, the fair sharing entails each reader waits approximately TX\_ON before transmission.

The behavior of the twenty baseband systems all subjected to -74dBm carrier sensing are examined. The simulations have been carried out for 320sec period with 1msec time resolution. Since the unit transmission time for each reader is 500msec (TX\_ON), the duration corresponds to 640 time frames. We derive the average normalized delay from the 640 time frames simulation.

Twenty subcarrier systems, which represents all the reader is subcarrier system using either channels 2 or 8, are also computed for the comparison. In the twenty subcarrier system, the odd number reader uses channel 2 to transmit while the even number reader uses channel 8. To account for the harmful interference into the subcarrier, the simulator measures the power level of the backscatter channels, channels 3 and 7, before transmissions in channel 2 and 8, respectively. The threshold level -50dBm for the receive channel carrier sensing is determined such that the backscatter from a 1.25m separated tag (-35dBm) can be protected by 15dB CIR (Figure 15).

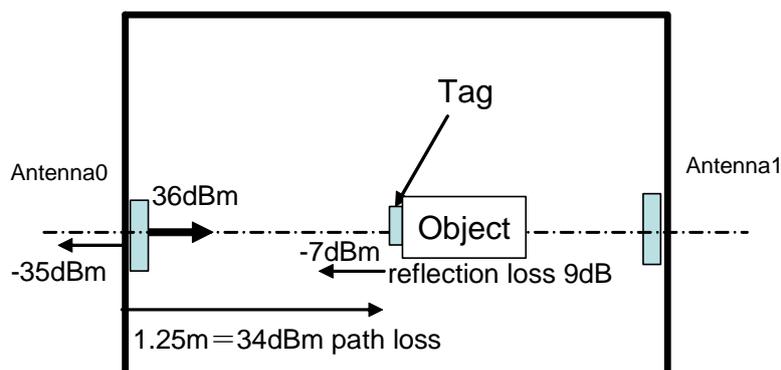


Figure 15 Subcarrier channel signal level.

Figure 16 shows the normalized delay of all baseband and all subcarrier systems. Each baseband system incurs approximately 1.2 normalized delay, which can be easily understood since we have 20 readers over 9 channels yielding 1.2 delay ( $20/9 - 1$ ) without frequency reuse. The delay in the perimeter reader is relatively short because the interference comes from only one side of the readers. On the other hand, there is practically no delay in twenty subcarrier systems. It is, therefore, shown that frequency efficiency could significantly be improved if we can introduce twenty subcarrier systems, which is usually only possible in new installations and the full renovation of the existing baseband system.

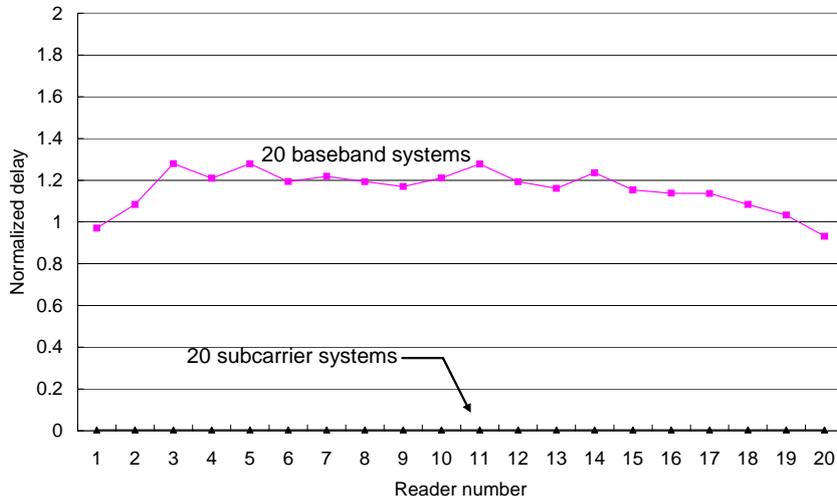
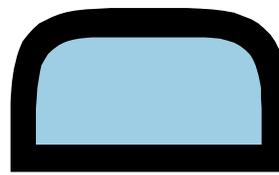


Figure 16 Exclusive baseband and subcarrier systems

Next, we examine a case where the left 10 readers in Figure 12 are subcarrier system and the right 10 readers are baseband system. The odd and even number subcarrier system uses channel 2 and 8 for transmission, respectively. The corresponding subcarrier are supposedly in channel 3 and channel 7. In this case, since each baseband system searches every channel, including subcarrier channels, for transmission, there is a possibility for baseband system to override subcarrier channel. The computed normalized delay is shown in Figure 17.

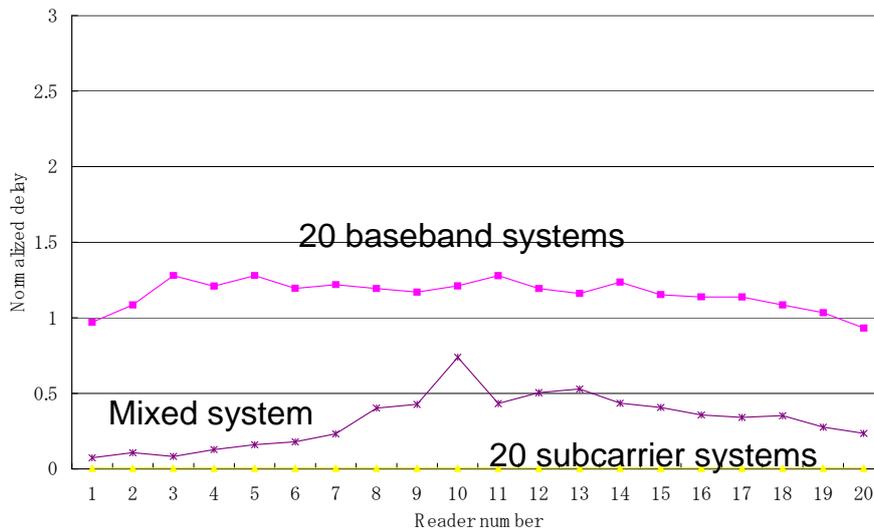
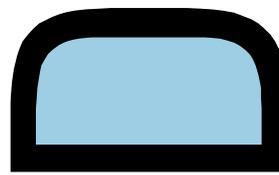


Figure 17 Baseband and subcarrier system mixed operation



It is shown that a mixed operation of baseband and subcarrier systems may lead the loss of frequency efficiency particularly for subcarrier systems which are geographically close to baseband system (reader 10, for example). The mixed operation works favor for baseband system because the 10 subcarrier system virtually reducing the number of readers contending for transmission channel (7 channels for 10 readers,  $10/7-1 = 0.4$ ) from the perspective of baseband system. The transmission channel history of reader 11 is shown in Figure 18

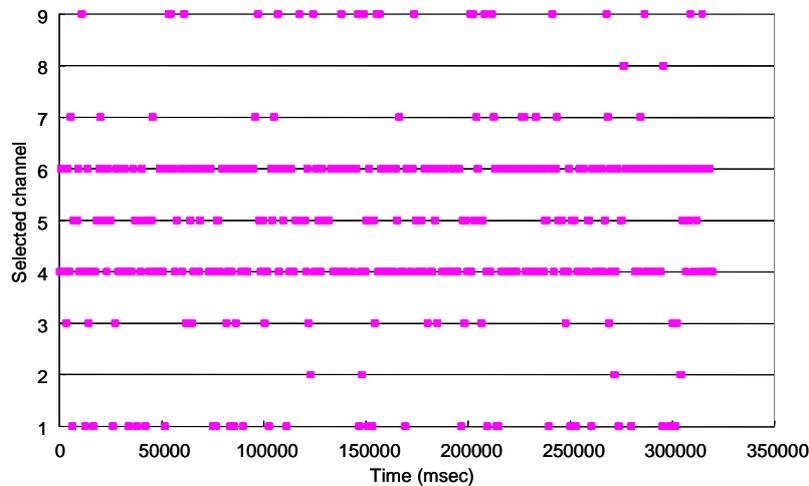


Figure 18 Transmission channel history of Reader 11

It is shown that Reader 11 hardly acquire channel 2 and 8, which are occupied by multiple subcarrier systems. The acquisition of the subcarrier channels 3 and 7, is also difficult for Reader 11, which is close to subcarrier system, because of the outband emission of the subcarrier readers. On the other hand, the involvement of subcarrier channels increases in Reader 20 (Figure 19), which has longer separation distance than that of Reader 11 from the subcarrier systems.

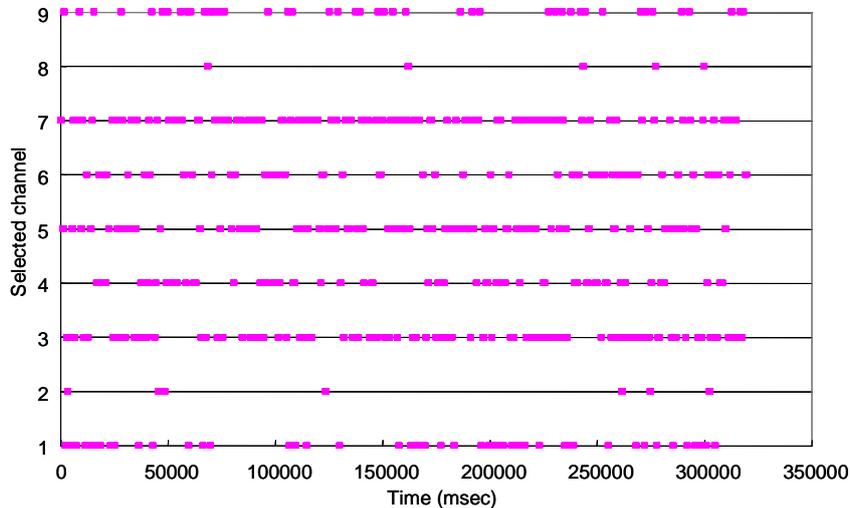
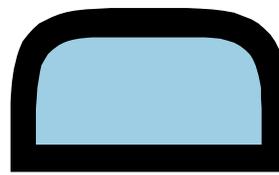


Figure 19 Transmission channel history of Reader 20

When a baseband system acquires and transmits in the subcarrier channel, the contending subcarrier system needs to wait until the subcarrier channel is clear. This should be the mechanism of large transmission delay in Reader 10 in Figure 17. As explained earlier, the transmission delay is equivalent to the packet error in the real implementations.

To protect the boundary subcarrier system fairly, we need to divide the whole channel into subcarrier system channels and baseband system channels. The reasonable grouping may be channels 1 to 3 to subcarrier system and the rest channels are for baseband system (Figure 20).

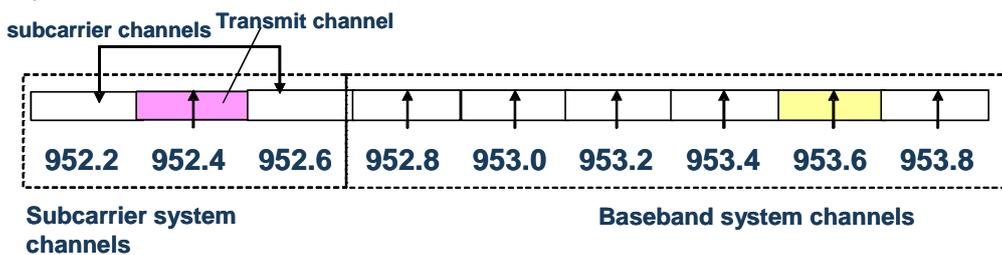


Figure 20 Channel grouping

The normalized delay of this arrangement is shown in Figure 21.

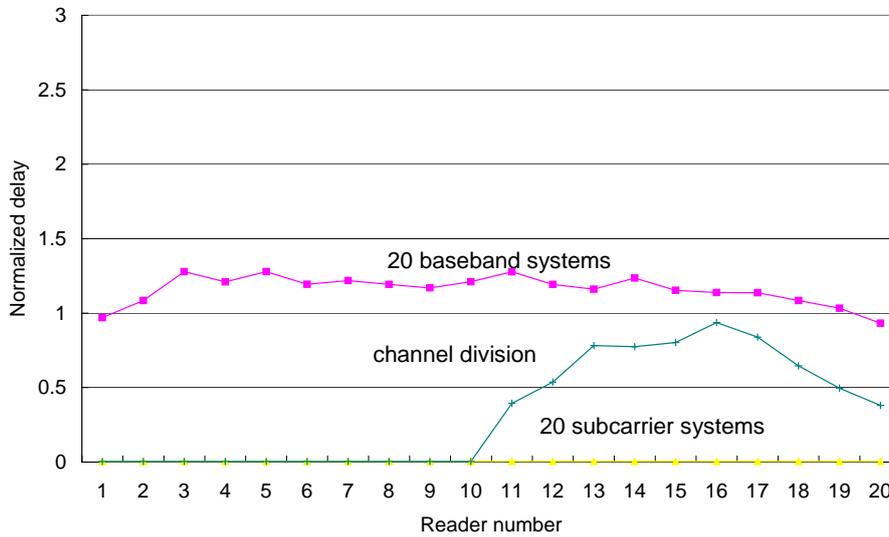
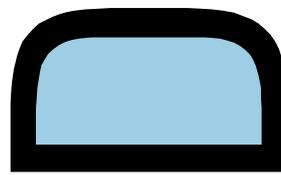


Figure 21 Channel division

The delay of the subcarrier system due to the channel division is negligible in this case while the division also mitigates the delay in the baseband system. This is because the number of interfering readers which contends with a baseband system virtually decreases since the ten subcarrier systems share the same channel.

The subcarrier systems, however, experience interference at the tag receiver, since this frequency division forces ten subcarrier systems to transmit only in one channel. The worst CIR (signal to Interference Ratio) at the tag for baseband system and the subcarrier system is shown in Figure 22.

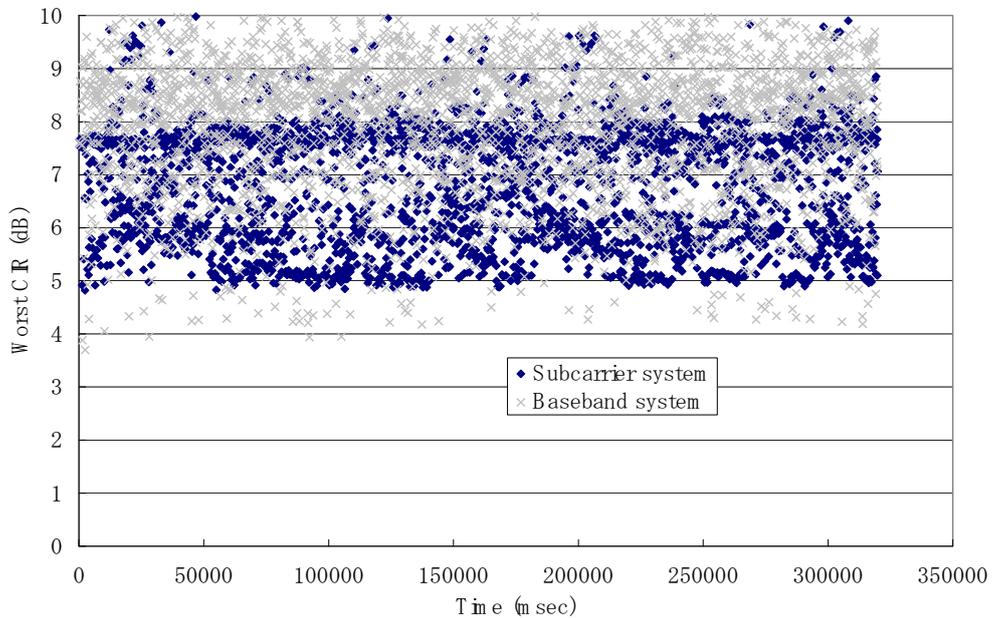
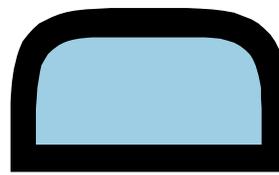


Figure 22 Worst CIR

The worst CIR of the subcarrier systems populated densely in less than 8dB area while that of baseband system is relatively dispersed although the CIR level is equivalent. It seems, therefore, the tag confusion is not the sole problem of one channel transmission subcarrier system but also in baseband systems.

Still, since the automatic protection of subcarrier system from tag confusion is of our interest, we evaluate the performance of carrier sensing enabled subcarrier system whose carrier sensing threshold is largely relaxed from the current regulation, -74dBm. In this case, the carrier sense is performed in the reader to tag communication link, since the purpose of the carrier sense in subcarrier system is exclusively to mitigate tag confusion problem. We have examined three threshold level, -42dBm, -32dB and -27dB. The threshold level -42dB is deduced from the sufficient CIR at tag receiver presuming the inference comes from the boresight direction(Figure 23).

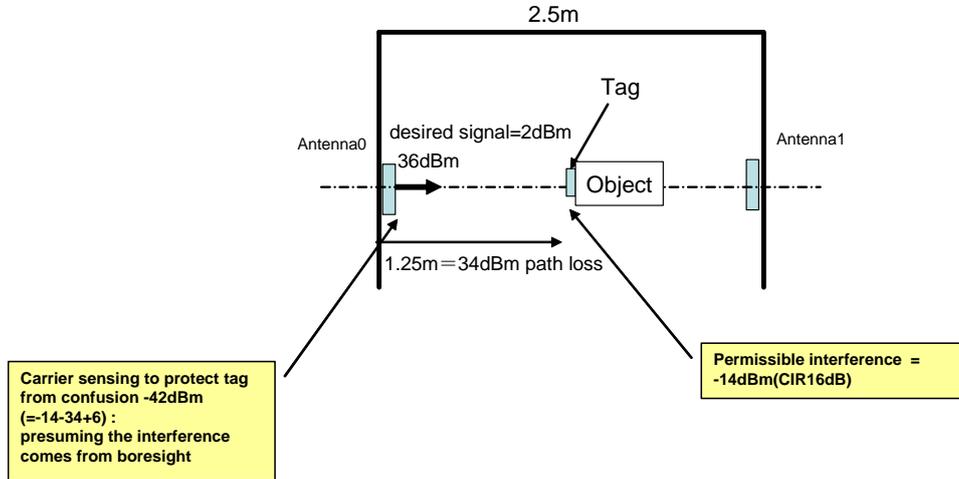


Figure 23 Carrier sense enabled subcarrier

The normalized delay for carrier sense enabled subcarrier system is shown in Figure 24.

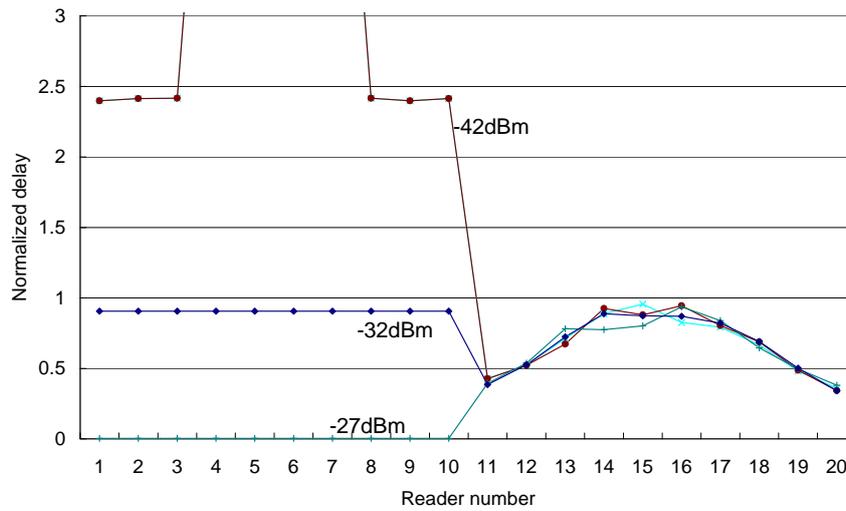


Figure 24 Carrier sense enabled subcarrier system

The corresponding worst CIR at tags for subcarrier system are shown in Figure 25 .

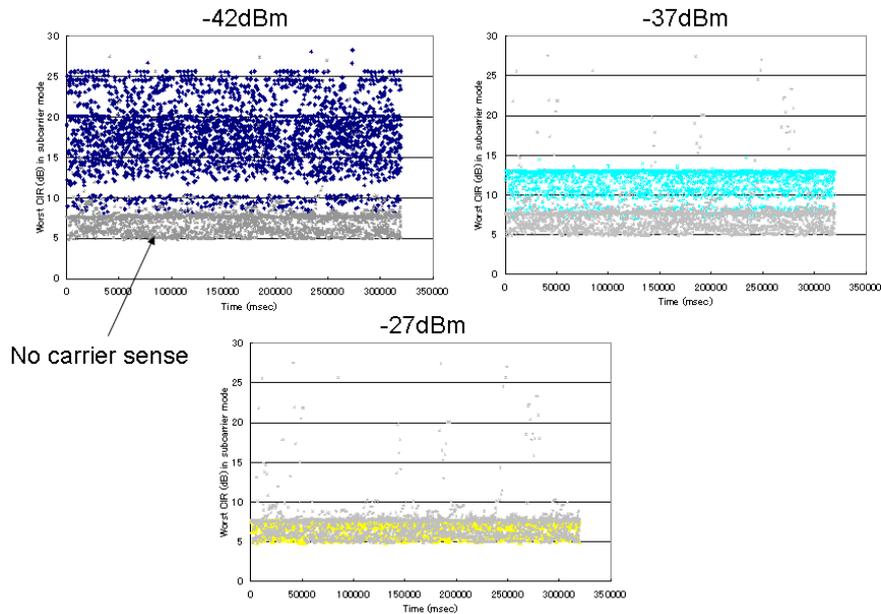
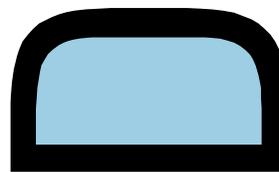


Figure 25 Worst CIR in carrier sense enabled subcarrier system

It is shown that the CIR at tag can be significantly improved when a carrier sense enabled subcarrier is employed. But we must endure a severe transmission delay in this case. The extreme case can be found in -42dBm carrier sense enabled subcarrier system in Figure 24. It is revealed that readers 4, 5 and 6 cannot transmit within ten normalized time frames. This is worse than -74dBm carrier sense with baseband system. It should be noted that even the average CIR improves with carrier sense enabled subcarrier system, the CIR variation increases. It is observed that the range of CIR is wider as stringent threshold is used as in Figure 25. The carrier sense enabled subcarrier system, therefore, cannot guarantee the avoidance of tag confusion. When we look at the delay of the baseband system in Figure 24, the normalized delay is consistent regardless of the carrier sense level of the carrier sense enabled subcarrier system. The carrier sense enabled subcarrier, thus, results in possible avoidance of tag confusion with transmission delay and does no good to the neighbor baseband system. Carrier sense enabled subcarrier system thus cannot be recommended.

## 4. Conclusion

Carrier sensing before transmission is generally a good idea to share frequency spectrum among different wireless systems. If the number of available channels is limited, however, the carrier sensing may cause transmission delay which could be a fatal problem to high power UHF RFID systems which require high speed inventory in a dense reader environment. The subcarrier coding in the tag to reader communication link is a powerful technology to mitigate the interference problem in densely populated UHF RFID systems. Subcarrier coding

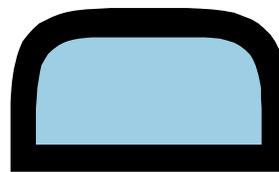


enables plural readers transmit simultaneously with one channel. The subcarrier system can be, thus, operated without carrier sensing. The baseband coding UHF RFID system, on the other hand, should be protected by carrier sensing because the transmitting and backscatter signal share the same channel in the TDD (Time Division Duplex) manner. Considering the existing implementation of baseband system and the industrial demand for dense reader environment, mixed operation of baseband and subcarrier system is likely to happen. In this paper, the performances in the mixed operation are evaluated in view of the transmission delay using MAC simulations.

An impetuous mixed operation of subcarrier system and baseband system entails the performance degradation in the subcarrier system in the vicinity of baseband system since the weak subcarrier backscatter cannot be sufficiently protected by the carrier sensing. The transmission from baseband system, even after carrier sensing, may override the subcarrier backscatter. Alternatively the subcarrier system need to wait until the subcarrier channel is clear or simply loose packets in the tag to reader communication link. The mixed operation, thus, works favour for baseband system since the number of available channels increase for the baseband system as plural subcarrier system transmit on one channel. If a portion of frequency spectrum is assigned exclusively to subcarrier system, the degradation of subcarrier system can be mitigated because baseband systems cannot exploit the backscatter channel. This frequency separation also improves the baseband systems' performance because the number of the contending readers is virtually decreased. .

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