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Interference Reduction Scheme for UHF Passive RFID Systems Using Modulation Index Control

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***Abstract*—Performance of UHF-band passive RFID system in a dense multi-reader environment is limited by both the reader-to-reader interference and reader-to-tag interference. In this paper, we firstly propose a combination of a subcarrier modulation backscattering and a reduced carrier frequency offset among readers to reduce both the reader-to-reader interference and the reader-to-tag interference. Then, we propose a new distributed modulation index control scheme using a tag's SINR estimation at readers in order to further reduce the reader-to-tag interference. By adaptively controlling the each reader's transmission modulation index, the asymmetric reader-to-tag interference can be effectively controlled to satisfy the required SINR of tags. Computer simulations show that the proposed scheme can reduce the minimum required inter-reader distance or increase the number of concurrently operable readers in dense multi-reader environments, especially when there is large unbalance among the reader-to-tag interferences on tags.**

I. Introduction

Radio frequency identification (RFID) systems have been taken great attention of industry which allows identification, tracking and management of wide variety of objects. Passive RFID systems using UHF-band of 860-960 MHz enable identification from distances up to several meters which are longer than those of RFID systems using other frequencies such as 13.56 MHz, and therefore, have been gathering much interest in recent years.

For UHF RFID systems, the reader-to-reader interference (R-R interference) and the reader-to-tag interference (R-T interference) are major problems which degrade the reading/writing performances in dense reader environments [1]. The R-R interference problem can be mitigated by frequency division multiple access (FDMA) techniques such as the listen-before-talk (LBT) via carrier sensing on multiple frequency channels [2], [3], frequency hopping [4] and tag backscattering using subcarrier modulation [5]. The LBT and the frequency hopping are effective only when the available number of channels is large enough for frequency reuse among multiple readers. These schemes are not effective for the R-T interference if available frequency bandwidth is not enough because tags have poor frequency selectivity. Use of the subcarrier modulation for tag's backscattering is an effective solution with higher spectrum efficiency than those of above two schemes. By setting the subcarrier frequency well apart from the interrogation signal spectrum transmitted by readers, the R-R interference can be suppressed by bandpass filtering of the received signal in the reader. However, this scheme is also not effective for the R-T interference because all the readers use the same channel for their interrogations.

For the R-T interference mitigation, a few approaches have been proposed so far. Simple centralized time scheduling schemes such as round-robin scheduling have been used for small reader networks [6]. A more complex centralized control scheme is proposed in [7] where hierarchical control nodes learn the collision patterns of readers and assign frequency over time to the synchronized readers. These time scheduling schemes require synchronization among readers and its operation becomes more difficult in a large reader network. In addition, for reading of moving tags such as objects on a conveyor belt, the time scheduling approach might result in failure in the reading. Another approach is to use multiple frequency channels which are well apart from each other, e.g. 1 MHz separation. This approach requires wide frequency band which lowers the spectrum efficiency. In dense reader environments, the R-R interference and the R-T interference should be controlled separately by using a combination of several schemes like the above.

In this paper, we firstly show that reducing carrier frequency offset among readers in combination with a subcarrier modulation backscattering can reduce both the R-T interference and the R-R interference in dense reader environments. Then, we propose a novel distributed adaptive modulation index control scheme for reader transmission in order to further reduce the R-T interference. We present simulation results that the proposed scheme can greatly increase the number of the survived readers by effectively controlling the R-T interference on victim tags especially when there is large unbalance among the R-T interferences on these tags.

In Section II, we describe the R-T interference problem of the passive RFID system. The proposed algorithm is given in Section III. In Section IV, we demonstrate the performance of our proposed algorithms by simulations. Finally, we give conclusions in Section V.

II. R-T interference problem

As stated in the previous section, readers' transmission signals using any frequency channels could cause the R-T interference because passive tags have poor frequency selectivity. It is important to note that co-channel signals might also be major component of the R-T interference due to its relatively larger carrier frequency drift to the interrogation signal bandwidth. ASK modulated signal has usually a large spectrum peak at the carrier frequency. This means that when the carrier frequencies of interfering readers have offset from that of the intended reader, the

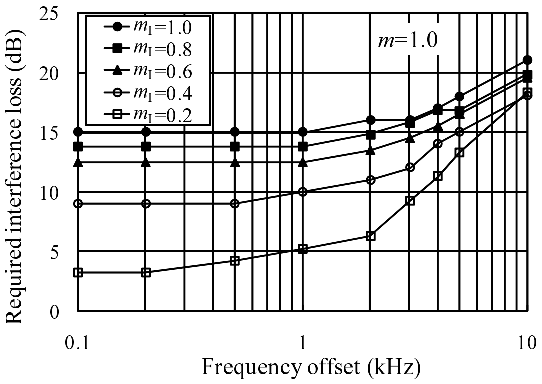

Fig. 1. Required R-T interference insertion loss vs. frequency offset for m=1.

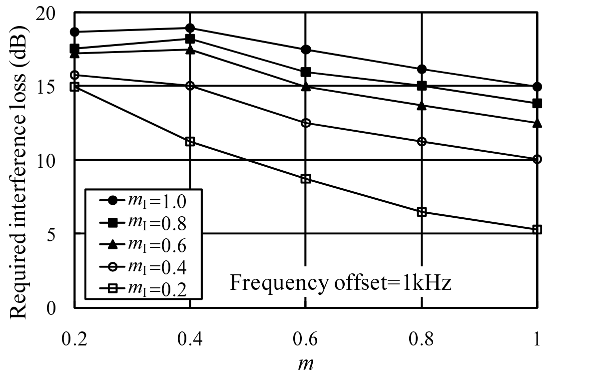

Fig. 2. Required R-T interference insertion loss vs. m for frequency offset of 1 kHz.

tags experience large R-T interference even if the interference signals are unmodulated tones [8]. Radio regulations in many countries permit the maximum carrier frequency drift of ±20 ppm for reader transmission which causes harmful beat interference to tags.

We evaluate how the frequency offset, the modulation index of the intended reader (m) and the modulation index of the interfering reader (m_I) affect the receiving performance of tags. A two-reader model is assumed here where one reader is interfering with another victim reader. Fig. 1 shows an example of tag immunity (required interference loss) against the frequency offset as a function of m_I for m=1. For reader's interrogation, double sideband (DSB) ASK modulation with 40 kbps and carrier frequency of 953 MHz are used. The transmission power of each reader is 36 dBm EIRP (Effective isotropically radiated power). It can be seen that frequency offset should be less than about 1 kHz, i.e. within ±1 ppm deviation to suppress the degradation within 2 dB. Therefore, minimization of the frequency offset of each reader within ±1 ppm can contribute to reduce the R-T interference and this is our first proposed solution to reduce the R-T interference. This can be realized by using an oscillator with high frequency stability. It is noted that such oscillators with about ±1 ppm stability can be commercially available without much cost increase. In case of large frequency offset, carrier frequency component dominates the R-T interference level and the spectrum side-lobe level determined by the modulation index has relatively small influence on that. However, when each reader has smaller frequency offset, the modulation index of the reader transmission has larger impact on the R-T interference level at nearby tags. Fig. 2 shows an example of required interference loss versus m as a function of m_I when frequency offset is 1 kHz. As can be seen from this figure, larger the modulation index is, larger the interference immunity of tags becomes due to the increased SINR but it also increases the interference to other tags interrogated by the other readers. This implies that an appropriate control of the modulation index of each reader can improve the system performance in the R-T interference-limited conditions.

III. Modulation index control

If SINR of tag's received signal can be known by the reader, the modulation index can be controlled. However, the tags usually do not have any measurement functions in it because priorities in the passive tag design are its cost and the power consumption. So, how to estimate the SINR of the remote tags by the reader is a key issue to be resolved. We propose to estimate the tag's SINR from the received backscattered signal from the tags.

For tag backscattering, passive tag modulates the received carrier signal by changing its reflectivity. Therefore, interference signals at the tag are also backscattered to the reader. This implies that the SINR of the tag can be measured from the backscattered signal. The received signal of the j_kth tag $r_{j_k}(t)$, the transmission signal of the j_kth tag $s_{j_k}(t)$ and the received signal of the i_kth reader $r_{i_k}(t)$ at time t are given by,

$$r_{j_k}(t) = G_{i_k j_k} s_{i_k}(t) + \sum_{\substack{r=1\\ r\neq k}}^{N} G_{i_r j_k} s_{i_r}(t) + \eta_{j_k}(t), \qquad (1)$$

$$s_{j_k}(t) = \rho\, b_{j_k}(t)\, r_{j_k}(t), \qquad (2)$$

$$r_{i_k}(t) = G_{j_k i_k} s_{j_k}(t) + \sum_{\substack{r=1\\ r\neq k}}^{N} G_{i_r i_k} s_{i_r}(t) + \eta_{i_k}(t), \qquad (3)$$

where $s_{i_k}(t)$ is the transmission signal of the i_kth reader, $b_{j_k}(t)$ is the response data signal modulated by the subcarrier and N is the number of the readers. $G_{i_k j_k}$, $G_{j_k i_k}$ and $G_{i_r i_k}$ are the propagation gains including the antenna gains from reader i_k to tag j_k, from tag j_k to reader i_k, and from reader i_r to reader i_k, respectively. The reflection efficiency ρ (or radar cross-section [6]) of the tag depends on the antenna size, the antenna's impedance matching and the tag's power consumption, etc. The noise components in the received signal of the tag j_k and of the reader i_k are denoted by $\eta_{j_k}(t)$ and $\eta_{i_k}(t)$, respectively.

We evaluate the SINR estimation performance of a reader interrogating a tag where the distance between the reader and the tag is 5 m. It is assumed that there is one interfering reader where the distance from the victim reader is D. The boresights of the reader's antennas face each other as the worst scenario. By using subcarrier backscattering, the R-R interference, the second term of the right-hand side of (3), can be effectively suppressed. However, the SINR estimation performance depends on the R-R interference level at the subcarrier frequency band. We find that the out-of-band emission level of a

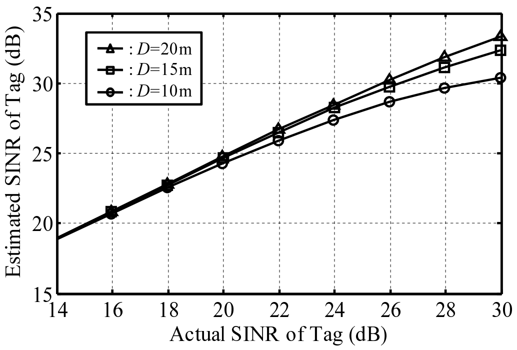

Fig. 3. Estimation performance of tag's SINR.

reader at the subcarrier frequency band should be less than -40 dBm/100 kHz for $D \geq 10$ m in order to sufficiently estimate the SINR. This is a rather harsh requirement for a cost-effective reader implementation. However, the requirement can be relaxed by avoiding the faced-boresight deployment. Use of a different polarization antenna from the nearest reader's antenna can also relax the requirement. Fig. 3 shows simulated performance of the SINR estimation for D=10 m, 15 m and 20 m. As can be seen from this figure, there is a fairly linear relation between the actual SINR and the estimated SINR for $D \geq 10$ m. This implies that an accurate SINR estimation can be done whenever tags can backscatter the responses. For encoding and modulation scheme of the interrogation signal of reader, we use the Manchester-coded ASK modulation which is used in some RFID standards [5]. The first spectrum-sidelobe power P_i of this signal with the modulation index m_i for reader i can be calculated as follows [9],

$$P_i(m_i) = \int_0^{\frac{4\pi}{T_b}} \left(\frac{Am_i}{1+m_i}\right)^2 T_b \,\mathrm{sinc}^2\left(\frac{\omega T_b}{4}\right)\sin^2\left(\frac{\omega T_b}{4}\right) d\omega, \tag{4}$$

where T_b is the symbol length and A is the amplitude of the ASK modulated signal. Instead of the direct control of the modulation index m_i, it is easier to control the sidelobe power P_i due to its linear relationship with the SINR. The proposed update algorithm is based on Foschini's standard power control algorithm [10] and is as follows,

$$P_i^{(t+1)} = \begin{cases} (\delta\,\bar{\gamma}_i/\gamma_i)\,P_i^{(t)} & \text{if } \gamma_i \geq \bar{\gamma}_i, \\ \delta P_i^{(t)} & \text{if } \gamma_i < \bar{\gamma}_i, \\ P_i^{(t)} & \text{if no tag,} \end{cases} \tag{5}$$

$$m_i^{(t+1)} = f\left(P_i^{(t+1)}\right), \tag{6}$$

where γ_i is the estimated SINR of the tag i, $\bar{\gamma}_i$ is the target SINR, δ is a constant larger than 1 and $f(x)$ is the inverse function of $P_i(m_i)$. When $\gamma_i < \bar{\gamma}_i$, the tag can not receive the interrogation command correctly then it does not reply to it. Reader can know this SINR condition by confirming no response from tags and then increases $P_i^{(t)}$ by δ, though the reader can not estimate the tag's SINR from the response signals. The modulation index m should be in a range of $m_{min} \leq m \leq m_{max}$ where m_{min} and m_{max} are the minimum and the maximum value of m, respectively. Therefore, there is the following constraint on $P_i^{(t)}$,

$$P_{min} \leq P_i^{(t)} \leq P_{max}, \tag{7}$$

where P_{min} and P_{max} are P_i for the m_{min} and m_{max}, respectively. When the calculated $P_i^{(t+1)}$ by (5) is not in the range of (7), it is replaced by the corresponding edge value.

When tags experience large interference or there is no tag in the interrogation field of the reader, the reader receives no response to the interrogation commands. The reader can not distinguish these two cases when having no response. A solution for this problem is to use an object sensor which detects the existence of objects with tags. Such systems are widely used in actual UHF RFID applications in order to turn off the reader emission when there is no object in the read range. Here, we assume that readers always know whether there are tags to be read in the reading range by using the object sensor. A solution without using such sensors are left for our future study. So, the reader which receives no response but knows the tag existence can assume that the interference level is high at the tags.

In the proposed algorithm, when m reaches the maximum value m_{max} and still $\gamma_i < \bar{\gamma}_i$, the reader transmission is turned off. We propose to employ a p-persistent turn-off procedure for such a case, i.e. the reader turns its transmission off with probability of $p < 1$.

$$P_i^{(t+1)} = \begin{cases} 0 & \text{if } p_i(t) \leq p, \\ P_i^{(t)} & \text{if } p_i(t) > p, \end{cases} \tag{8}$$
$$\text{if } \gamma_i < \bar{\gamma}_i,\ P_i^{(t)} = P_{max},$$

where $0 < p_i(t) \leq 1$ is the uniform random number polled by reader i at time t. This will result in the less number of the unnecessary turned-off readers than the case of $p = 1$ because a reader's turn-off will improve the SINR of other ill-conditioned tags interrogated by another reader.

We examine the convergence of our power control algorithm in (5), (7) and (8) by using the canonical power control theorem [11]. A power control algorithm of reader i is called canonical if the followings are satisfied:

1) The interference measure is *standard*;
2) The target region is *closed*;
3) The update algorithm is *bounded* and *reactive*.

The interference measure is standard because our algorithm is based on Foschini's standard power control algorithm. The target SINR region $[\bar{\gamma}_i, \bar{\gamma}_i]$ is closed. The bounding condition of the algorithm is as follows,

$$\max\left(P_{min},\ \min\left(P_i^{(t)},\ (\delta\,\bar{\gamma}_i/\gamma_i)\ P_i^{(t)}\right)\right) \leq P_i^{(t+1)}$$
$$\leq \min\left(P_{max},\ \max\left(\delta P_i^{(t)},\ (\delta\,\bar{\gamma}_i/\gamma_i)\ P_i^{(t)}\right)\right). \tag{9}$$

The reactive condition of the algorithm when the SINR is not in the target SINR region is as follows,

$$\left|\frac{P_i^{(t)}}{P_i^{(t+1)}} - 1\right| > \epsilon, \tag{10}$$

where $\epsilon > 0$. Under the reactive condition, the SINR is not allowed to stay outside the target region indefinitely. From the constraint of (10), it is obvious that the reactive condition cannot be satisfied when $P_i^{(t+1)}$ reaches P_{min} or P_{max}. By turning-off the transmission of the readers which do not satisfy the reactive condition, the algorithm

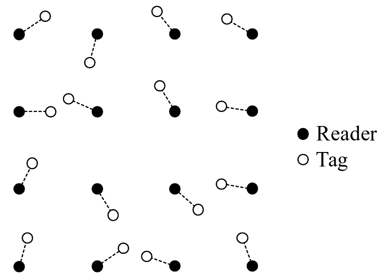

Fig. 4. 4 × 4 square-grid reader deployment model (N=16).

TABLE I
SIMULATION PARAMETERS.

Path loss exponent	2
Carrier frequency	950–956 MHz
Frequency channel	Single channel (200 kHz/channel)
Reader deployment	2-reader model, 4 × 4 square-grid model
Tag location	5 m at the boresight of the reader antenna
Reader antenna	6 dBi gain, 60 degree of 3 dB beam width, Uniformly random direction for the square-grid model
Tag antenna	0 dBi gain, Omni directional
Reader transmission	36 dBm EIRP, Adjacent channel: -40 dBm/100 kHz, No frequency offset, No carrier sensing
Tag transmission	Subcarrier backscattering at adjacent channels
Tag reflection efficiency	$\rho = -10$dB
Target SINR	$\bar{\gamma} = 9$ dB
Modulation index range	$0.2 \leq m \leq 1.0$
Algorithm parameters	δ = 1.26 (=+1dB), Update interval=10 ms
Number of trials	200 for the square-grid deployment with different antenna boresight combinations.

becomes canonical and its convergence of the survived readers to the target is guaranteed.

IV. Simulation results

A. Simulation Model

We evaluate the performance of our proposed algorithm by computer simulations. In our simulations, we use two deployment models of the readers and the tags. In the first experiment, a two-reader deployment model is used in order to evaluate what kind of cases the proposed algorithm works well. In the second experiment, we place 16 readers on a 4 × 4 square grid as shown in Fig. 4. Each reader's antenna direction is randomly selected with uniform distribution. Each reader communicates with a tag located in the direction at which the reader's antenna has its maximum gain. The distance between each reader and the interrogated tag is same for all the readers.

Table I summarizes the simulation parameters. Parameters of the carrier frequency and the maximum reader transmission power are based on the Japanese radio regulation for UHF-band passive RFID systems [2].

B. Two readers Deployment

This model uses two readers (Reader 1 and Reader 2) which interrogate Tag 1 and Tag 2, respectively. The antenna boresights of these readers are facing each other. An additional loss L_{21} is inserted only in the link from the Reader 2 to Tag 1 in order to simulate asymmetric R-T interference environments. When L_{21}=0 dB, each tag has the same R-T interference. For cases of $L_{21} > 0$ dB, Tag 2 has the larger R-T interference than that on the Tag 1.

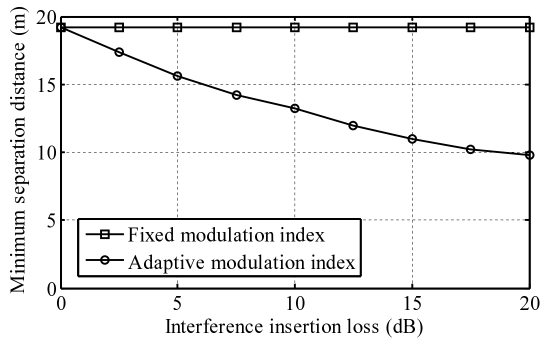

Fig. 5. Required minimum separation distance between two readers vs. interference insertion loss L_{21}.

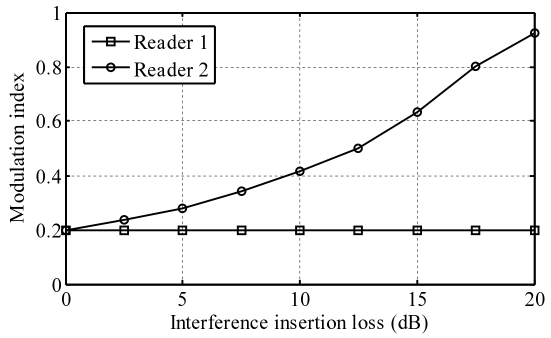

Fig. 6. Modulation index of readers for the proposed scheme after the algorithm convergence vs. interference insertion loss L_{21}.

We compare the performance of the proposed adaptive modulation index scheme and the fixed modulation index scheme for a single channel system. For the fixed modulation index case, each reader continuously interrogates the tag regardless of whether it can get the response from the tag or not. Fig. 5 shows the required minimum separation distance between the two readers versus the insertion loss L_{21}. The proposed scheme has large gain when there is large unbalance in their R-T interferences (asymmetric interference environment), where such situations are often observed in actual system deployments. Fig. 6 shows the converged modulation index value of each reader using the proposed scheme at the minimum separation distance. The modulation index of the Reader 2 becomes large while that of the Reader 1 stays around the minimum value of 0.2. It is noted that when L_{21}=0 dB (i.e. symmetric R-T interference environment), the proposed scheme has no gain in the required separation distance and the modulation indices of both readers converged to the minimum value of 0.2. The proposed scheme controls the modulation index of each reader to be the minimum value which satisfies the required quality. This feature will improve the maximum communication distance between the reader and the tag because it is easier for passive tags to generate more power for their activation from the received signal with

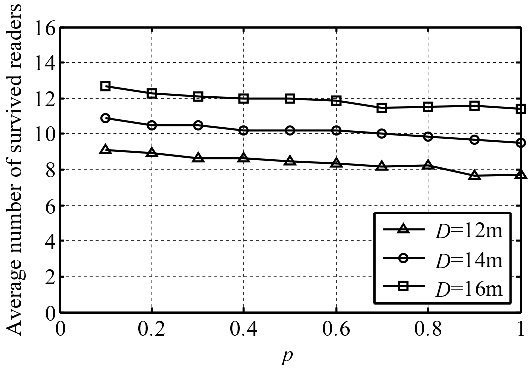

Fig. 7. Average number of survived readers vs. p for square-grid deployment.

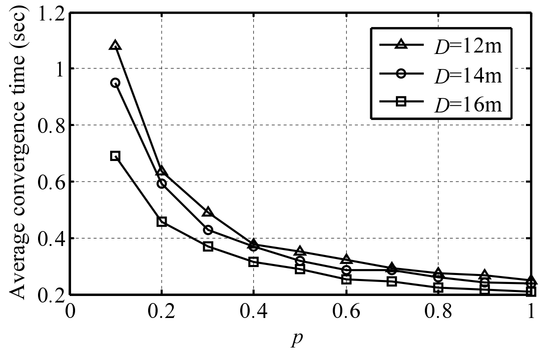

Fig. 8. Average convergence time vs. p for square-grid deployment.

lower modulation index. It is noted that the actual power transmission efficiency will also depend on each tag's rectifier design for its activation power generation.

C. Square-grid Reader Deployment

For the square-grid deployment, we evaluate average performances over 200 trials with different antenna directivity combinations. Firstly, we evaluate how the persistent probability p of the proposed p-persistent turn-off procedure affects on the performance. Figs. 7 and 8 show the average number of survived readers and the average convergence time of the algorithm versus the persistent probability p as a function of the minimum inter-reader distance D, respectively. By using small values of p, the average number of survived readers can be increased, however, which result in longer convergence time. Larger value of p will cause simultaneous turn-off of the ill-conditioned readers interfering each other. However, when one reader turns off, the SINR of the ill-conditioned tags interrogated by the neighbor readers may become high enough for communications. The use of small p could avoid such an unnecessary simultaneous turn-off of readers. In the following simulation, we use $p = 0.3$ which can achieve compromise between the performance (about 10% gain in the number of survived readers) and the convergence time (less than 0.5 sec). It is noted that the appropriate value of p will depend on the deployment model and its environment.

Fig. 9 shows the average number of survived readers for the proposed adaptive modulation index scheme and the conventional fixed modulation index scheme after the algorithm convergence as a function of the minimum inter-reader distance D. In dense reader environments, i.e. for small D, the proposed scheme can greatly increase the number of the survived readers. This implies that the proposed scheme can effectively control the R-T interference on victim tags in this deployment model.

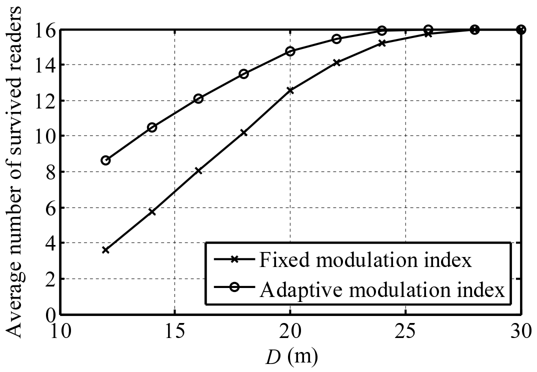

Fig. 9. Performance comparison of fixed and adaptive modulation index schemes for square-grid deployment.

V. Conclusion

In this paper, interference reduction scheme for UHF passive RFID systems using a combination of the subcarrier backscattering and the distributed adaptive modulation index control has been proposed. We show by computer simulations that the proposed scheme can reduce the minimum separation distance between readers or increase the number of concurrently operable readers in dense multi-reader environments, especially when there is large unbalance among the R-T interferences on tags. Our scheme allows a continuous interrogation to tags and an asynchronous operation among readers. These features are very beneficial for actual RFID system operations.

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