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# Adaptive and Probabilistic Power Control Algorithms for Dense RFID Reader Network

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# Adaptive and Probabilistic Power Control Algorithms for Dense RFID Reader Network

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*Abstract*—**In radio frequency identification (RFID) systems, the detection range and read rates may suffer from interferences between high power devices such as readers. In dense networks, this problem grows severely and degrades system performance. In this paper, we investigate feasible power control schemes to ensure overall coverage area of the system while maintaining a desired data rate. The power control should dynamically adjust the output power of a RFID reader by adapting to the noise level seen during tag reading and acceptable signal-to-noise ratio (SNR). We present a novel distributed adaptive power control (DAPC) and probabilistic power control (PPC) as two possible solutions. This paper discusses the methodology and implementation of both algorithms analytically. Both DAPC and PPC scheme are simulated, compared and discussed for further work.**

## I. Introduction

The advent of radio frequency identification (RFID) technology has brought with it, increased visibility into manufacturing process and industry. From supply chain logistics to enhanced shop floor control, this technology presents many opportunities for process improvement or re-engineering. The underlying principle of RFID technology is to obtain information from tags by using readers through radio frequency (RF) links. The basics of RFID technology and current standards can be found at [1].

In passive RFID systems, tags harvest energy from the carrier signal of the reader to power internal circuits. Moreover, passive tags do not initiate any communication but they only decode modulated command signals from the readers and respond accordingly through backscatter communication. The nature of RF backscatter requires high power ouput at the reader, theoretically higher output power offers further detection range with given bit error rate (BER). For 915 MHz ISM bands, the output power is limited to 1W according to [2]. When multiple readers are present in a working environment, signal from one reader may reach others and causes interferences. This RFID interference problem was first explained in [3] as the *Reader Collision*.

The work in [3] suggested that RFID *frequency interference* occurs when a signal transmitted from one reader reaches another and jams its ongoing communication with tags in range. Studies also show that, interrogation zones need not overlap for *frequency interference* to occur, the reason being power radiated by one reader needs only to be at the level of tag backscatter signal($\mu W$) [4] to cause interference when reaching others. For a desired coverage area, readers must be placed relatively close together forming a dense reader network. Consequently, *frequency interference* occurs which results in limited read range, inaccurate reads, and long reading intervals.

To date, *frequency interference* has been described as 'collision' as in a *yes* or *no* case where a reader in the same channel at a certain distance causes another reader not to read any tags at all. In fact, higher interference only implies that the read range is reduced significantly but not to zero. This result is mathematically proved in Section II. Previous attempts [5]-[6] to solve this problem were based on either spectral or temporal separation of readers. Colorwave [5] and 'Listen before talk' implemented as per CEPT regulations [6] rely on time-based separation while frequency hopping spread spectrum (FHSS) implemented as per the FCC regulations [2] utilize multiple frequency channels. The former strategy is inefficient in terms of reader on time and average read range while the latter is not universally permitted by regulations. The proposed work is specifically targeted for RFID networks to overcome these limitations.

In this paper, we propose two novel power control schemes which employ reader transmission power as the system control variable to achieve desired read range and data rate. Degree of interference measured at each reader is used to dynamically adjust transmission power. With the same underlying concept, adaptive power control uses signal-to-noise ratio (SNR) to adapt power at discrete-time steps while probabilistic power control adapts the transmission power based on probabilistic distribution.

In terms of organization, the paper discusses the problem formulation in section II. Then the power control algorithms are presented in section III and IV. In section V and VI, implementation of the algorithms and simulation setups are detailed. Subsequently, the simulation results are discussed.

## II. Problem Formulation

*Frequency interference* problem need to be fully understood before a solution can be evolved. In this section, we present analysis of the problem and assumptions made for our solution.

### A. Mathematical relations

In a backscatter communication system, SNR based on power must meet a required threshold $R_{required}$ which is decided by the tag encoding method and BER desired. The BER desired is evolved from a specified data rate for the system. For any reader $i$, the following must hold for successful tag detection

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$$\frac{P_{bs}}{I_i} = R_i \geq R_{required} \quad (1)$$

where $P_{bs}$ is the backscatter power from tag, $I_i$ is the interference at tag backscatter frequency, and $R_i$ is the SNR at reader.

In general, $P_{bs}$ can be evaluated in terms of the reader transmission power $P_i$ and the tag distance $r_{i\text{-}t}$. Other variables such as reader and tag antenna gains, modulation indexing and wavelength can be considered as constants and simplified in (2) as $K_1$. Then,

$$P_{bs} = K_1 \cdot \frac{P_i}{r_{i-t}^{4q}} = g_{ii} \cdot P_i \quad (2)$$

where $q$ is environment dependent considering path loss, and $g_{ii}$ represents the channel loss (gain) from reader $i$ to tag and back. Communication channel between the reader and interogated tag is considered relatively stable since it should be in direct line of sight and short range, for this reason Rayleigh fading is not considered for the reader-tag link. Hence, $P_{bs}$ can be evaluated using path loss ignoring any channel uncertainty.

Interference caused by reader $j$ at reader $i$ is given as

$$I_{ij} = K_2 \cdot \frac{P_j}{r_{ij}^{2q}} \cdot X_{ij}^2 = g_{ij} \cdot P_j \quad (3)$$

where $P_j$ is the transmission power of foreign reader $j$, $r_{ij}$ is the distance between the two readers, $K_2$ represents all other constant properties, and $X$ is a random variable with Rayleigh distribution to account for Rayleigh fading loss in the channel between reader $j$ to reader $i$. After simplification, $g_{ij}$ represents the channel loss (gain) from reader $j$ to reader $i$. Note that since the interference actually occurs at the tag backscatter sideband, power of reader $j$ at that particular frequency needs to be considered only. This factor is also accounted for in $K_2$ and $g_{ij}$.

Cumulative interference $I_i$ at any given reader $i$ is essentially the sum of interference introduced by all other readers plus the variance of the noise $\eta$ at the reader.

$$I_i = \sum_{j \neq i} g_{ij} P_j + \eta \quad (4)$$

Given the transmission power and interference, the maximum detection range of a reader is given by

$$r_{actual}^{4q} = \frac{K_1 \cdot P_i}{R_{required} \cdot I_i} \quad (5)$$

Considering the same power and interference, received SNR for a tag at desired range $r_d$ can be calculated as

$$R_{rd} = \frac{K_1 \cdot P_i}{r_d^{4q} \cdot I_i} \quad (6)$$

From (5) and (6), we can calculate the maximum detection range in terms of $R_{rd}$

$$r_{actual} = r_d \left( \frac{R_{rd}}{R_{required}} \right)^{1/4q} \quad (7)$$

For analysis purposes, we consider any tag within such range to be successfully detected by the reader. If a reader is completely isolated, meaning no interference, a maximum range $r_{max}$ can be achieved at maximum power $P_{max}$. In a practical situation, it is inappropriate to expect this maximum range. Taking this into consideration, desired range $r_d$ should be set to a value less then $r_{max}$.

Substitute (2) and (3) into (1), SNR as a time-varying function for a particular reader is given by

$$R_i(t) = \frac{P_{bs}(t)}{I_i(t)} = g_{ii} \cdot P_i(t) \Bigg/ \left( \sum_{j \neq i} g_{ij}(t) P_j(t) + \eta_i(t) \right) \quad (8)$$

Note that $g_{ii}$ is constant for a particular reader-tag distance.

If desired range for such reader is defined as $r_d$, we can define the SNR for the backscatter signal from a tag placed at $r_d$ as

$$R_{i-rd}(t) = \frac{P_{bs-rd}(t)}{I_i(t)} = g_{ii-rd} \cdot P_i(t) \Bigg/ \left( \sum_{j \neq i} g_{ij}(t) P_j(t) + \eta_i(t) \right) \quad (9)$$

where

$$g_{ii-rd} = \frac{K_1}{r_d^{4q}} \quad (10)$$

### *B. Simple Two Reader Model*

To understand some properties of the problem, a simple two-reader model can be considered. Given two readers $i$ and $j$ spaced $D(i, j)$ apart, each with desired range $R_{i\_1}$ and $R_{j\_1}$, shown in Fig. 1. Readers must provide power $P_i$ and $P_j$ to achieve the intended ranges without considering interference. However, due to the interference introduced by each other, the actual detection range reduces down to $R_{i\_2}$ and $R_{j\_2}$ respectively.

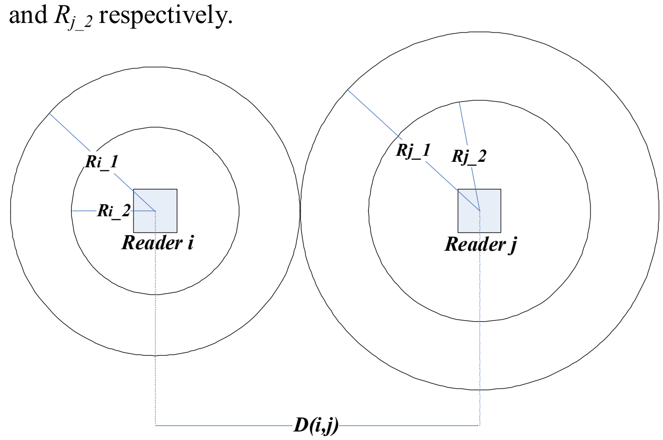


Fig. 1. A simple two reader model.

As a result of unacceptable SNR at a desired detection range, readers must attempt to increase their transmission power. If both readers greedily increase their powers, they will eventually reach the maximum power without achieving the desired range. One could solve the problem by operating them in mutually exclusive timeslots. However, as the number of readers increase, this strategy severely degrades each reader's average read time and detection range which are important in industrial applications.

A more appropriate solution would be to balance the transmission power between two readers. In the above model, if $i$ transmits at $P_{max}$ and $j$ is off, a read range greater than the targeted value $R_{i\_1}$ can be achieved. In this scenario, there exists a power level at which reader $j$ can transmit and still allow $i$ to achieve read range $R_{i\_1}$. This process can be applied in reverse to enable reader $j$ to achieve targeted range. In such a cycle, the average read range of both readers is improved over the on and off cycle. With dense networks, the effect of this improvement will be significant. Such yielding strategy is required in dense reader networks where desired range cannot be achieved on all readers simultaneously.

### C. Distributed Solution

In this paper, two schemes of distributed power control are proposed---adaptive power control (DAPC) and probabilistic power control (PPC). DAPC involves systematic power updates based on interference measurements. It also uses embedded channel prediction to account for the time-varying fading channel state for the next cycle. In Section III, we analytically show that the proposed DAPC scheme will converge to any target SNR value in the presence of channel uncertainties. For dense networks where the target SNR can not be reached by all readers simultaneously, a random back off method is incorporated introducing a degree of yielding to ensure that all readers achieve their desired range.

In PPC scheme, a probability distribution is specified for each reader to select output power from. Statistical characteristics for desired read range can be specified as a target. To achieve the above target, the output power distribution on each reader can be adapted based on interference measurements. The relationship between the two distributions is analytically derived in Section IV.

## III. Distributed Adaptive Power Control

Distributed power control (DPC) protocols have been extensively researched in the field of wireless communication, including ad-hoc networks and cellular networks. Power control in RFID reader network is similar to these protocols in concept. However, there are several fundamental differences between them due to the unique communication interface and applications for RFID.

First, the main goal for DPC in wireless communication is to conserve energy while maintaining quality of service (QoS) requirements. In [8]-[9], authors propose different algorithms on updating power to maintain a target SNR threshold for successful communication. The work proposed in this paper is to reduce interference introduced to others while maintaining read range requirements for each reader and thereby achieving optimal coverage for all readers. Secondly, DPC for ad-hoc and cellular networks requires feedback communications between the transmitter and receiver. In RFID reader networks the reader acts as a transmitter and receiver. Hence, the feedback is internal to the reader and does not result in any overhead. Finally, in contrast to low power wireless networks, RFID readers in dense networks may not achieve the target SNR even at maximum power owing to the high levels of interference. The proposed DAPC algorithm is built up on DPC scheme proposed for ad-hoc networks in [9]. We now demonstrate the performance of DAPC analytically.

### A. Power update scheme

Transforming (9) into the discrete time domain with $l$ representing each time step, we get (11) as the feedback equation for DAPC scheme

$$R_{i-rd}(l+1) = \alpha_i(l) R_{i-rd}(l) + \beta_i v_i(l) + r_i(l)\omega_i(l) \qquad (11)$$

where

$$\alpha_i(l) = 1 - \frac{\sum_{j\neq i} \Delta g_{ij}(l) P_j(l) + \Delta P_j(l) g_{ij}(l)}{I_i(l)} \qquad (12)$$

and

$$\beta_i = g_{ii-rd} \qquad (13)$$

and

$$v_i(l) = P_i(l+1)/I_i(l) \qquad (14)$$

and $\omega(l)$ is the zero mean stationary stochastic channel noise with $r_i(l)$ is its coefficient.

Considering channel uncertainty in (11), the SNR at the reader at time instant $l$ is a function of channel variation from time instant $l$ to $l+1$. Therefore, the channel variation must estimated using

$$\hat{\theta}_i(l+1) = \hat{\theta}_i(l) + \sigma\psi_i(l) e_i^T(l+1) \qquad (15)$$

where $\theta_i^T(l) = [\alpha_i(l) \;\; r_i(l)]$ is a vector of unknown parameters, $\psi_i(l) = \begin{bmatrix} y_i(l) \\ \omega_i(l) \end{bmatrix}$ is the regression vector, $\hat{\theta}_i(l)$ is the estimate of $\theta_i(l)$, $e$ is the error system and $\sigma$ is the adaptation gain. It is proven in [8] that the mean channel estimation error along with the mean SNR error converges to zero asymptotically if using (15) as the estimation equation.

### B. Random back off

In a dense reader environment as this algorithm is targeted for, it is inconceivable that all readers are able to achieve their required SNR together. These readers will eventually reach maximum power as a result of the power updates. This necessitates that a time-based yielding of some readers is required to allow others to achieve their target SNR. Thus, a random back-off policy is implemented in the algorithm. Whenever the reader finds the target SNR not achievable at maximum power, it falls off to lower target SNR after waiting for a random period of time. Since interference is a locally experienced phenomenon, multiple readers will face this situation and they will back off randomly. The rapid reduction of power will result in significant improvement of SNR at other readers. After sufficient readers have backed off, a reader in question will find it possible to achieve the required SNR. The random back off policy will cause only rapid negative changes in interference, and hence does not adversely affect the performance of the power update scheme.

### C. Need Variable

The above algorithm is generally dominated by readers which are placed in isolated areas since they manage to achieve their SNR and thus stay high most of the time interfering with all other readers. To introduce fairness in the algorithm, a need variable was designed in each reader. In this scheme, a reader keeps track of the number of time steps that have passed since it achieved the required SNR. This need variable is scaled and added to the random wait time that the reader waits during the back-off process, thus allowing a neglected reader to stay high while other readers in the vicinity fall back, allowing it to achieve the required SNR and therefore, the read range.

### D. DAPC implementation

DAPC can be easily implemented onto the MAC layer of the RFID reader. The algorithm requires two parameters to be known initially. These are the desired range $r_d$, and the required SNR $R_{required}$.

The power update can be seen as a feedback between the transmitter and receiver units of a reader. A block diagram of the implementation is shown in Fig. 2. Receiver sends interference feedback to the power update block. In the power update block, based on $r_d$, $R_{required}$, and $P(l)$, $R_{i\text{-}rd}(l)$ is calculated. Also, the power for the next step $P(l+1)$ is calculated. $P(l+1)$ is then limited to maximum power $P_{max}$, if the $P(l+1)$ greater than $P_{max}$, the random back off scheme is triggered, otherwise $P(l+1)$ is used as the output power for the next cycle. The random back off block acts as a count down timer once it is triggered; the count down starts from the sum of a random number and the need variable. A need variable block monitors the achieved SNR and skews the random back off time to enhance fairness. At the end of count down, the output of the reader is set to $P_{min}$. If at any time during the count down, $P(l+1)$ falls below $P_{max}$, the random back off is aborted.

Simulation and results of the above implementation are discussed in Section V and Section VI respectively along with those of PPC.

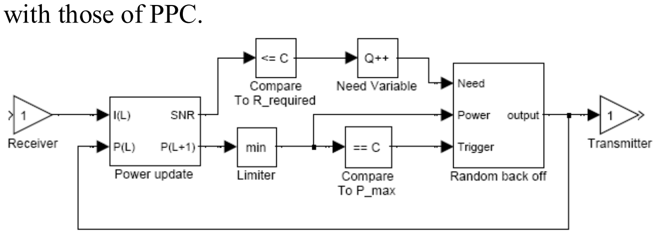


Fig. 2. Block diagram for DAPC implementation

## IV. Probabilistic Power Control

The idea of probabilistic power control comes from simple time slot allocation algorithms. If each reader is assigned a slot to transmit in full power while others are turned off, maximum range of that reader can be achieved. A round robin assignment of time slots can assure that all readers operate with no interference. However, this is inefficient in terms of average read range, reader utilization, and waiting periods. It is obvious that more than one reader can operate in the same time slot but at different power levels to accomplish better overall read range. If the power levels at all readers change in each time slot, over time, every reader will be able to achieve its peak range while maintaining a good average.

For a distributed solution, this would involve setting a distribution for power to be picked from for each time step. Such a distribution would need to be adapted based on the density and other parameters of the reader network.

### A. Power Distribution

Equation (8) states that the read range of a particular reader is dependent on its transmission power and the interference experienced which is a function of powers of all other readers. If power of all readers follows certain probability distribution, the distributions of read ranges of all readers are functions of these power distributions.

$$F(r_i) = f_i(F(P_1),...,F(P_n)) \quad \forall \quad i \in [1,n] \tag{16}$$

where $F(r_i)$ is the cumulative density function of read range of reader $i$, and $F(P_i)$ is the cumulative power density function of reader $i$. Performance metrics including mean read range $\mu_r$ and percentage of time $\tau_r$ achieving desired range $r_d$ characterized the read range distribution $F(r_i)$.

$$F(r_i) = g_i(\mu_r, \tau_r) \tag{17}$$

To achieve targeted characteristics on the read range distribution, we need to modify the power distribution freely. Beta distribution is specifically chosen for this reason; by specifying the shape variables $\alpha$ and $\beta$, one can change the cumulative density function in the domain from 0 to 1 (0% to 100% power). By changing these two parameters, we can control the power distribution and thus attempt to achieve desired targets on the read range distribution in (16).

$$F(P_i) = I_{p_i}(\alpha, \beta) \tag{18}$$

### B. Distribution Adaptation

Equation (16) represents the relationship between the cumulative density function of read range and power of a reader. However, in a distributed implementation, operation parameters such as the power distribution and location of a reader are not known to the other readers. Hence, these parameters have to be reflected in a measurable quantity; Equation (4) provides such a representative quantity in the form of interference which leads to (19).

$$F(r_i) = l_i(F(P_1), F(I_i)) \tag{19}$$

Substituting (17) and (18) into (19),

$$g_i(\mu_r, \tau_r) = l_i(I_{p_i}(\alpha, \beta), F(I_i)) \tag{20}$$

Transforming (20), we can represent $\alpha$ and $\beta$ in terms of $\mu_r$, $\tau_r$, and $F(I_i)$.

$$[\alpha, \beta] = h_i(\mu_r, \tau_r, F(I_i)) \tag{21}$$

$F(I_i)$, the cumulative density function of interference, can be statistically evaluated by observing the interference level at each reader over time. It can also be interpreted as the local density of around the reader.

The function represented by (16) involves joint distributions of multiple random variables, it is complex and difficult to extract. However, it is easy to obtain numerical data sets of the above function from simulation. Such data sets can be used to train a neural network which could provide a model of the above function. In this paper, we do not attempt to provide an interference based adaptive distribution tuning scheme for the PPC. We only implement PPC using a fixed power distribution for all scenarios to observe the overall performance patterns. The fixed distribution consists of $[\alpha,\beta]=[0.1\ \ 0.1]$ which is tuned for highly dense scenarios.

## V. Simulation Setup

The simulation environment was set up in MATLAB. Full model of DAPC and PPC are implemented for comparison. Both algorithms are tested under the same configurations.

### A. Reader design

Power of the reader is a floating point number which scales from 0 to 10 with 10 being the largest. Other system constants are designed so that the maximum read range of a reader in isolated environment is 3 meters. Interference experienced at any reader is calculated based on a matrix consisting of power and positions of all other readers plus the channel variation $g_{ij}$. A desired range of 1.5 meters is specified based on the worst case analysis.

### B. Simulation Parameters

For both models, random topologies are generated for given densities and number of nodes. The density of the scenario is given by the minimum distance between two readers and the maximum size of the coordinates. The minimum distance varies from 3 meters to 14 meters and the maximum size of the coordinate is adjusted accordingly. The number of nodes is set from 5 to 60 for scalability testing of the algorithms. Simulation for each scenario is run for 10000 iterations.

### C. Evaluation metrics

To evaluate the performances of the algorithms, the following metrics are compared: average read range, and percentage of time achieving desired range. Standard deviation and mean of the above metrics are evaluated across all readers in each scenario. We now present the results of the simulation.

## VI. Results and Analysis

In terms of average detection range, DAPC is seen to have superior performance over PPC for a dense network (minimum distance between readers is 3 meters) as shown in Fig. 3.

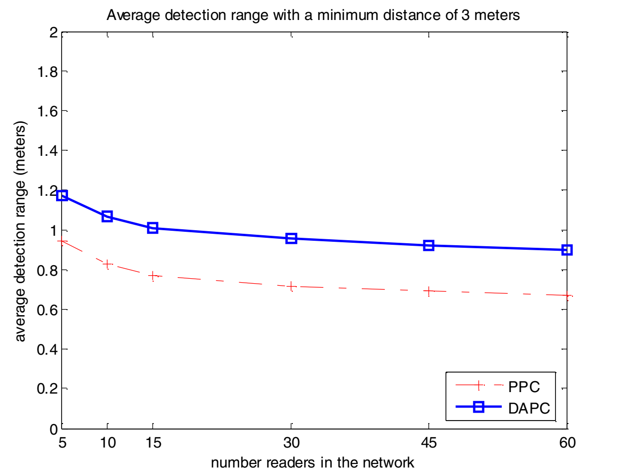


Fig. 3. Average detection range vs. number of readers for minimum distance between readers set to 3 meters.

In terms of achieving the required range for a given density of nodes (minimum distance between nodes is 4 meters), DAPC offers better performance for fewer nodes but much worse in large scale dense network. It is also shown that PPC scales better than DAPC as its performance degrades much slower in larger networks (Fig. 4).

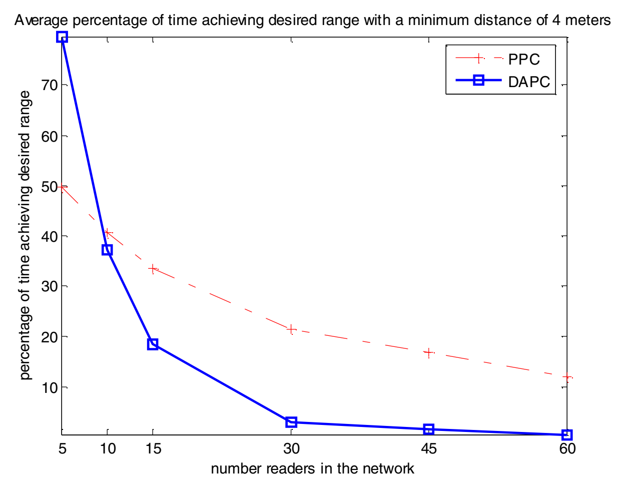


Fig. 4. Percentage of time for which desired range is achieved for minimum distance between readers set to 4 meters.

We now compare the average range and percentage of time for which the desired range is achieved for a fixed number of readers with varying density.

In Fig. 5, we set the number of readers to 60 and vary the minimum distance between readers from 3 through 14 meters. It is seen that the average detection range of DAPC is better in dense networks though the performance of the two schemes are closer in sparse scenarios.

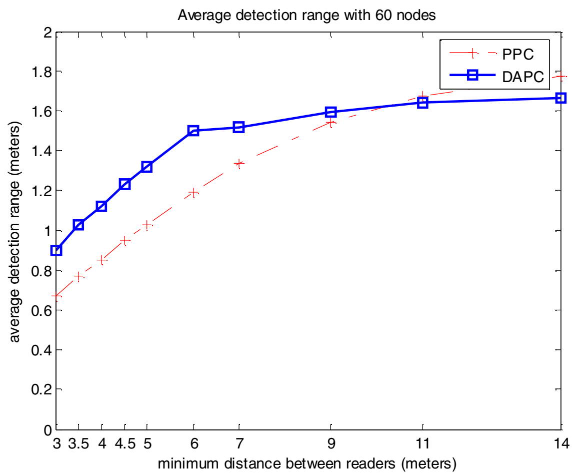


Fig. 5. Average detection range for 60 readers in network

Similarly, we compare the percentage of time for which the desired range is achieved for a network of 40 readers for minimum distance varying from 2 through 14 meters. At high densities, PPC offers superior results in achieving the desire range as it is tuned for dense RFID network. As mentioned in Section IV, PPC implemented here is tuned for dense networks, the performance in achieving desire range peaks out in sparse networks. In contrast, DAPC achieves 100% of desired range in sparser networks. This evidently demonstrates the correctness of DAPC power update scheme and channel estimation.

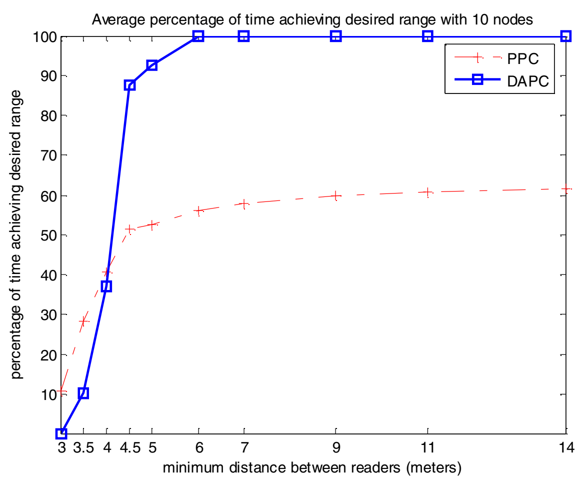


Fig. 6. Percentage of time for which desired range is achieved for a network of 10 readers.

## VII. Conclusions

Two algorithms for RFID reader read range improvement and interference management based on distributed power control are explored and analyzed. Both algorithms show promising results. DAPC is seen to converge at a fast rate to the required SNR if it is achievable within power limitations. In this paper, we have provided a novel interpretation of the *reader collision* problem which can be applied to other similar RF systems also. Further work on DAPC would involve automatically tuning the random backoff and need variable implementations based on interference measurements. Further work on PPC would concentrate on developing a method to internally adapt the power distribution based on interference measurements to achieve specified statistical goals for the read range.

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