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Decentralized Power Control with Implementation for RFID Networks

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Abstract— **In radio frequency identification (RFID) systems, the detection range and read rates will suffer from interference among high power reading devices. This problem grows severely and degrades system performance in dense RFID networks. In this paper, we investigate a suite of feasible power control schemes to ensure overall coverage area of the system while maintaining a desired read rate. The power control scheme and MAC protocol dynamically adjusts the RFID reader power output in response to the interference level seen locally during tag reading for an acceptable signal-to-noise ratio (SNR). We present novel distributed adaptive power control (DAPC) and probabilistic power control (PPC) as two possible solutions. A generic UHF wireless testbed is built using UMR/SLU GEN4-SSN for implementng the protocol. Simulation and hardware results are included.**

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 RFID technology basics and current standards can be found at [1].

In passive RFID systems, tags harvest energy from the carrier signal which is obtained from 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 [2]. The nature of RF backscatter requires high power ouput at the reader and theoretically higher output power offers farther detection range with a desirable bit error rate (BER). For 915 MHz ISM bands, the output power is limited to 1W according to [3]. When multiple readers are deployed in a working environment, signals from one reader may reach others and cause interference. This RFID interference problem was explained in [4] as the *Reader Collision*.

The work in [4] 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 among readers need not overlap for *frequency interference* to occur, the reason being power radiated from one reader needs to be at the level of tag backscatter signal(μW) [5] to cause interference when reaching others. For a desired coverage area, readers must be placed relatively close to one another forming a dense reader network. Consequently, *frequency interference* normally occurs which results in limited read range, inaccurate reads, and long reading intervals. Placement of readers to mimize the interference and maximize the read range is an open problem.

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 of its tags in its range. In fact, higher interference only implies that the read range is reduced significantly but not to zero. This result is mathematically given in Section II. Previous attempts [6]-[7] to solve this channel access problem are based on either spectral or temporal separation of readers. Colorwave [6] and "Listen before talk" implemented as per CEPT regulations [7] rely on time-based separation while frequency hopping spread spectrum (FHSS) implemented as per the FCC regulations [3] utilizes multiple frequency channels. The former strategy is inefficient in terms of reader 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 a desired read range and read rates. Degree of interference measured at each reader is used as a local feedback parameter to dynamically adjust its transmission power. With the same underlying concept, decentralized adaptive power control uses interference measurements and signal-to-noise ratio (SNR) estimates to adapt transmission power at discrete-time steps while probabilistic power control adapts the transmission power based on certain probability distribution. A Lyapunov-based approach is used to show the convergence of the proposed DAPC scheme. Both schemes are simulated and DAPC is implemented on hardware. The results demonstrate theoretical conclusions.

II. PROBLEM FORMULATION

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

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In a passive backscatter RFID system, SNR of the return signal from the tag at the reader must meet a required threshold $R_{required}$, which can be expressed as

$$R_{required} = (E_b/N_0)/(W/D) \tag{1}$$

where E_b is the energy per bit of the received signal in watts, N_0 is the noise power in watts per Hertz, D is the bit rate in bits per second, and W is the radio channel bandwidth in Hertz. For a known modulation method and BER (bit-error-rate), E_b/N_0 can be calculated. Hence, $R_{required}$ can be selected based on a desired data rate and BER.

For any link *i*, the following must hold for successful reception

$$\frac{P_i}{I_i} = R_i \geq R_{required} \tag{2}$$

where P_i is the received signal power from the tag, I_i is the interference at the signal frequency, and R_i is the SNR at the receiver.

In general, P_i can be expressed in terms of the RFID reader transmission power P_t and two-way channel gain factor g_{ii} which includes path loss, Rayleigh fading, shadowing and other channel uncertainties of the path from the RFID reader to the tag at distance r_d from the reader and back.

$$P_i = g_{ii} \cdot P_t \tag{3}$$

Interference experienced at receiver *i* caused by all other RFID readers operating in the same frequency channel is given by

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

where g_{ij} is the channel loss from reader *j* to redaer *i*, and η is the variance of noise.

By substituting equations (3) and (4) into (2), the SNR of the backscatter signal from a tag at distance r_d, as a time-varying function at a particular receiver can be given by

$$R_i(t) = \frac{P_i(t)}{I_i(t)} = g_{ii} \cdot P_t(t) \Big/ \left(\sum_{j \neq i} g_{ij}(t) P_j(t) + \eta_i(t) \right) \tag{5}$$

In addition, given the level of interference, the actual read range of the RFID reader can be calculated as

$$r_{actual} = r_d \left(\frac{R_{i-rd}}{R_{required}} \right)^{1/4q} \tag{6}$$

where $R_{i\text{-}rd}$ is the estimated SNR for a tag at distance r_d from the reader based on the observed interference level.

Based on equation (6), the objective for DAPC is to select $P_t(t+1)$ which will provide $R_{i-rd}(t+1)$ equal to $R_{required}$. The difficulties for power control in presence of channel uncertainties is that $g_{ii}(t+1)$, $g_{ij}(t+1)$ and $P_j(t+1)$ are unknown. Proposed DAPC uses a novel channel estimation scheme to successfully predict the effect of these parameters in the next time interval. A Lyapunov-based approach is used to show the convergence of the proposed DAPC scheme.

A. Distributed Solution

In this paper, two schemes of distributed power control are introduced --- adaptive power control (DAPC) and probabilistic power control (PPC). DAPC involves systematic power updates based on local interference measurements at each reader. It also uses embedded channel prediction to account for the time-varying fading channel state for the next cycle. In Section III, we present the proposed DAPC scheme that 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, an addition *selective back-off* method is incorporated besides power updates introducing a degree of yielding to ensure that all readers achieve their desired range.

By contrast, in PPC scheme, a probability distribution is specified for each reader to select output power from. Statistical distribution for the desired read range can be specified as the target. To achieve the target, the output power distribution on each reader is altered 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) schemes have been extensively studied in the field of wireless communication, including in ad-hoc networks [14] and cellular networks [13]. Conceptually, power control in a RFID reader network is similar to these protocols. However, there are several fundamental differences between them due to the unique nature of the communication interface and RFID application.

In [11]-[14], authors propose different power updating schemes aimed at maintaining a target SNR threshold for successful communication whereas, the work proposed for RFID systems is to reduce interference introduced by others while maintaining read range requirements thereby achieving optimal coverage and read rates for all readers. In addition, DPC for ad-hoc and cellular networks requires feedback signal between the transmitter and receiver. In RFID reader networks, the reader acts both as a transmitter and receiver. Hence, feedback is internal and does not result in any communication overhead. Third, in contrast to low power wireless networks, RFID readers in dense networks may not achieve the target SNR even at maximum power owing to high levels of interference from other readers. Finally, in contrast with a connection oriented network where each node transmits only when it is needed, most RFID readers are required to be always on in order to read the tags. Therefore, it is difficult to distribute channel access among all readers.

The proposed DAPC algorithm consists of two building blocks---*adaptive power update* and *selective back-off*. The goal of the *adaptive power update* is to achieve required SNR with an appropriate output power by correctly estimating the interference and any channel uncertainties. In dense networks, *selective back-off* forces high power readers to yield so that other readers can achieve required SNR. We now discuss these two building blocks of DAPC in depth.

A. Power update scheme

In discrete time domain, the feedback control for DAPC is selected as

$$p_i(l+1)=\frac{I_i(l)}{g_{ii}(l)}\left[-\hat{\theta}_i(l)R_i(l)+R_{required}+k_v\left(R_i(l)-R_{required}\right)\right] \tag{7}$$

where $\hat{\theta}_i(l)$ is the estimation of the unknown parameters defined as $\theta_i(l)$, and k_v is a control parameter. The mean channel estimation error along with the mean SNR error converges to zero asymptotically, if parameter updates are taken as

$$\hat{\theta}_i(l+1)=\hat{\theta}_i(l)+\sigma R_i(l)\left(R_i(l)-R_{required}\right) \tag{8}$$

where σ is the adaptation gain.

Theorem 1: Given the DPC scheme above with channel uncertainties, if the feedback from the DPC scheme is selected as (9), then the mean channel estimation error along with the mean SNR error converges to zero asymptotically, if the parameter updates are taken as in (8)

$$v_i(l)=\beta_i^{-1}\left[-\hat{\theta}_i(l)\psi_i(l)+\gamma+k_v e_i(l)\right] \tag{9}$$

Then the mean error in SNR and the estimated parameters are bounded. ■

The selection of k_v and σ should obey the following,

$$\sigma\left\|R_i(l)\right\|^2<1 \tag{10}$$

$$k_{v\max}<\sqrt{1-\sigma\left\|R_i(l)\right\|^2} \tag{11}$$

Analytical proof of convergence of the DAPC algorithm is provided in [16]

B. Selective back-off

In a dense reader environment, it is inconceivable that all readers are able to achieve their target SNR together due to severe congestion which affects both read rates and coverage. These readers will eventually reach maximum power as a result of the *adaptive power update*. This demands a time-based yielding strategy of some readers to allow others to achieve their target SNR.

Whenever the reader finds the target SNR is not achievable at maximum power, meaning the interference level is too high in the network, it should back-off to a low output power for a period of time. Since interference is a locally experienced phenomenon, multiple readers will face this situation and they will all be forced to back off. The rapid reduction of power will result in significant improvement of SNR at other readers. After waiting for the back-off period, a reader will return to normal operation and attempt to achieve the target SNR. The process is repeated for every reader in the network. To fairly distribute the channel access among all congested readers, certain quality measurements must be ensured for all readers in the back off scheme. The *selective back-off* scheme uses the percentage of time a reader has achieved desired range as the quality control parameter to ensure the fairness.

After backing off, each reader must wait for a time duration τ_w. In order to show the illustrate the effect of back off, τ_w is defined as a logarithm function of the percentage of time ρ a reader has attained the required SNR. A neglected reader will exit back-off mode quickly and attain the required SNR while other readers in the vicinity fall back. The calculation of τ_w is given by

$$\tau_w=10\cdot\left[\log_{10}(\rho+0.01)+2\right] \tag{12}$$

Using the above equation, a reader with ρ equals 10% will wait for 10 time intervals while the waiting time for ρ of 100% equals 20. A plot of waiting time τ_w versus ρ is presented in Fig. 1.

The back-off policy will cause negative changes in interference, and hence does not adversely affect the performance of the adaptive power update.

C. DAPC implementation

DAPC can be easily implemented at the MAC layer of the RFID reader and MAC implementation is not covered in detail in this paper. The algorithm requires two parameters to be known initially. These are the desired range r_d, and required SNR $R_{required}$. Next the PPC is discussed.

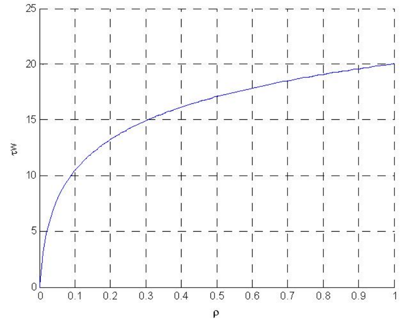

Fig. 1. Selective back-off function plot.

IV. PROBABILISTIC POWER CONTROL

The idea of probabilistic power control comes from simple TDM algorithms. If a reader is assigned a time slot to transmit in full power while others are turned off, it will achieve its maximum range. 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 following certain distribution, over time, every reader will be able to achieve its peak range while maintaining a good average.

A. *Power Distribution*

Equation (6) 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 reader powers follow certain probability distribution, the distribution of read ranges for each reader is a function of these power distributions

$$F(r_i) = f_i(F(P_1),...,F(P_n)) \tag{13}$$

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 μ_r and percentage of time ρ achieving desired range r_d characterized the read range distribution $F(r_i)$.

$$F(r_i) = g_i(\mu_r, \rho) \tag{14}$$

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 α and β, one can change the cumulative density function in the domain from 0 to 1 (0% to 100% power). Power using Beta distribution can be represented as

$$F(P_i) = H(P_i : \alpha, \beta) \tag{15}$$

B. *Distribution Adaptation*

Equation (13) represents the relationship between the cumulative density function of read range and output power of all readers. 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 (6) provides such a representative quantity in the form of interference which leads to (16) as

$$F(r_i) = l_i(F(P_1), F(I_i)) \tag{16}$$

Substituting (14) and (15) into (16),

$$g_i(\mu_r, \tau_r) = l_i(H(\alpha,\beta), F(I_i)) \tag{17}$$

Transforming (17), we can represent α and β in terms of μ_r, ρ, and $F(I_i)$ as

$$[\alpha,\beta] = h_i(\mu_r, \rho, F(I_i)) \tag{18}$$

where $F(I_i)$, 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 around the reader.

The function represented by (18) involves joint distributions of multiple random variables and 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 potentially to train a neural network which could provide a model of the above function. In this paper, we do not attempt to provide the interference based adaptive distribution tuning scheme for the PPC. We only implement PPC using fixed power distributions for all scenarios to observe the overall performance patterns and to understand the differences between the DAPC and PPC. The two distributions, $Beta(0.1, 0.1)$ and $Beta(2, 2)$ are chosen for the simulation and compared for performance evaluation.

V. SIMULATION RESULTS AND ANALYSIS

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

A. *Reader design*

Reader power is implemented as a floating point number varying from 0 to 30dBm (1W) as per FCC regulation. For error-free detection, the reader should maintain a target SNR of 14 (~11dB). 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 2 meters is specified based on the worst case analysis.

For proposed DAPC, *power update* parameters Kv and σ are both set to 0.001. For proposed PPC, both $Beta(0.1, 0.1)$ and $Beta(2, 2)$ are implemented. Only these fixed Beta distributions are evaluated in the analysis of Probabilistic Power control.

B. *Simulation Parameters*

For both models, random topologies are generated in order to emulate denser network with suitable number of readers. The RFID network with suitable density for a given scenario is created by placing the readers with the minimum distance between them and the maximum area under test. The minimum distance between any two readers is varied from 4 meters to 14 meters and the maximum size of the coordinate is adjusted accordingly. The number of readers is changed from 5 to 60 for creating denser network and to test the scalability of the proposed schemes. Each simulation scenario is executed for 10000 iterations.

C. *Evaluation metrics*

To evaluate the performances of the proposed algorithms, the following metrics: average read range, percentage of time attaining desired range, average output power, and average interference experienced are evaluated across all readers for each scenario and simulation results are given. The percentage of time achieving the desired read range and average read range are of maximum priority while the transmission power level is a secondary metric.

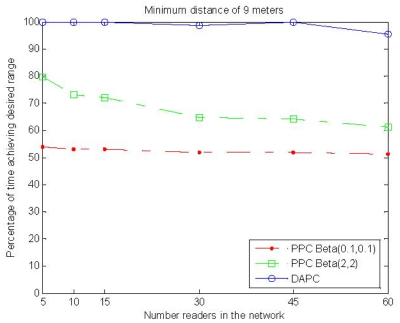

Fig. 2. Number of readers vs. percentage of time achieving desired range.

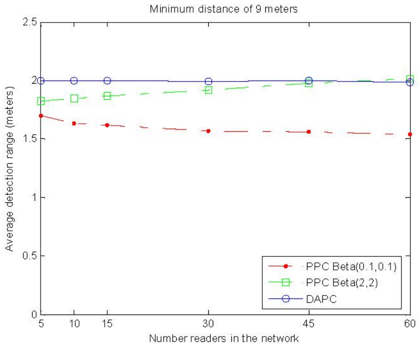

Fig. 3. Number of readers vs. average detection range in meters.

The analysis of performance in sparse networks is discussed first. With the minimum distance of 9 meters between any two readers, the average percentage of time ρ attaining desire range across all readers is presented in Fig. 2. Note that each reader has a maximum detection range of 3 meters without interference and the desired range is set to 2 meters in the presence of multiple readers. DAPC is observed to have superior performances over the two PPC algorithms for this sparse network. DAPC converges to 100% desired range achievement with the appropriate parameter estimation and closed-loop feedback control described in Section III. The results justify the theoretical conclusions. It is also shown that $Beta(2,2)$ performs better than $Beta(0.1,0.1)$ in terms of ρ. With $Beta(2,2)$ distribution, every reader will be on and transmitting at medium power most of the time. With sparse networks and small interferences, the medium power overcomes the interference produced and therefore achieving desired range. In contrast, $Beta(0.1,0.1)$ has a 30% probability being off, therefore the probability of attaining desired range will be lower.

In Fig. 3, considering the average detection range for the same scenario, DAPC converges to the 2 meters desired range and outperforms both PPC algorithms. We can also observe the average power level used for each algorithm in Fig.4. Since the mean for both $Beta(2,2)$ and $Beta(0.1,0.1)$ is 0.5, the average reader output power lays at 500mW which is half of the maximum power. Meanwhile, DAPC is able to dynamically adjust its output power to find the optimal level for which desired range can be achieved as the size of the network varies.

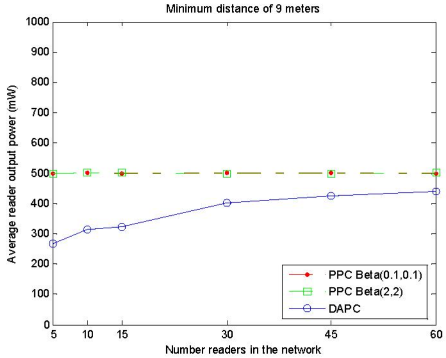

Fig. 4. Number of readers vs. Average output power per reader.

HARDWARE ARCHITECTURE

In this section, an overview on the hardware implementation of the DAPC protocol is given. First, a customized test platform for evaluating DAPC is presented.

Test platform

Fig. 5. Hardware block diagram.

In order to evaluate various networking protocols, a UHF wireless test platform is designed based on the UMR/SLU Generation-4 Smart Sensor Node (G4-SSN). Silicon Laboratories® 8051 variant microprocessors was selected for its ability to provide fast 8-bit processing, low-power consumption, and ease of interfacing to peripheral components. ADF7020 ISM Band transceiver was employed as the underlying physical radio for its ability to provide precise control in frequency, modulation, power, and data rate. A Zigbee compliant Maxstream XBee™ RF module was also employed as a secondary radio unit providing alternative wireless solutions. A block diagram of the hardware setup is shown in Fig. 5. A picture of the hardware in use is shown in Fig. 6.

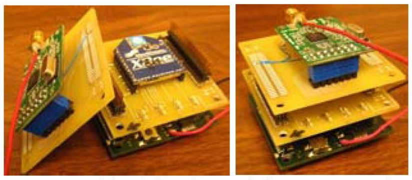

Fig. 6. Gen-4 SSN with Zigbee layer (left), ADF7020 layer (right).

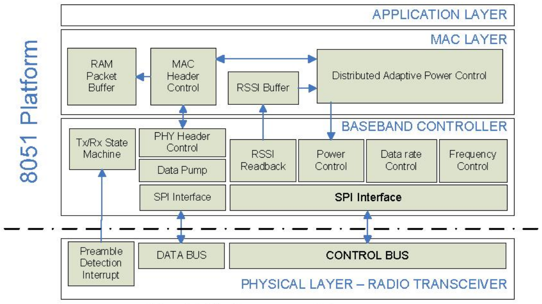

Fig. 7. Software architecture.

Fig. 7 represents the software architecture in use. The DAPC scheme is implemented at the MAC layer and provides a control input to the BB to control the transmission power levels.

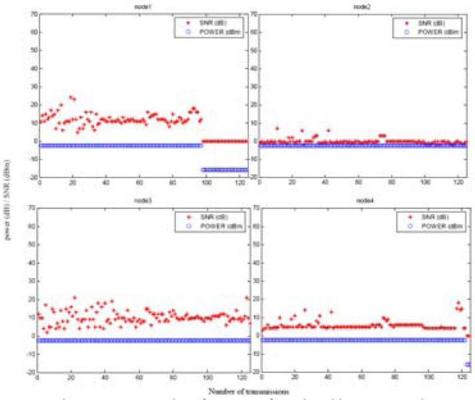

Fig.8. SNR and power levels in 4 reader network without power updates.

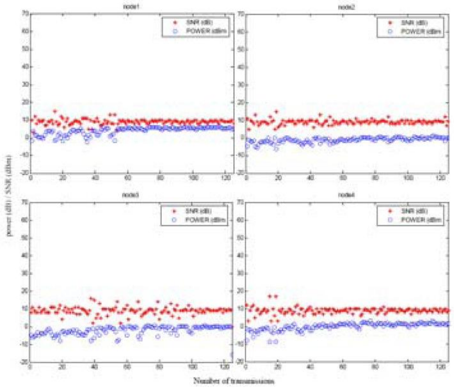

Fig.9. SNR and power levels in 4 reader network with DAPC.

RFID reader networks with 4 readers are implemented using the Gen-4 SSN setup. The desired SNR for the readers is at 10dB and channel attenuation between the tag and reader is assumed to be 40dB (g_{ii}). First, a system with no power control scheme is tested, and the output power of all four readers is set to be -2dBm. In Fig. 8, the performances of all readers are shown and it is clear that two of the readers never achieve desired SNR and others have unstable SNR.

A network of readers with DAPC implementation is then tested in the same setup as the uncontrolled case. Shown in Fig. 9, all four readers reach the desired SNR of 10dB at various power levels.

VI. CONCLUSIONS

Two algorithms for RFID reader read range and interference management based on distributed power control are explored and analyzed. Both algorithms can be implemented as power control MAC protocols for MATLAB based RFID reader network simulation as well as hardware experiments. DAPC is seen to converge at a fast rate to the required SNR if it is achievable within power limitations. Selective back-off algorithm in DAPC enhances the channel utilization in denser networks. PPC is not fully implemented to tune in with the network density, however it still shows advantages in scalability and fairness of channel assessment. Hardware implementation of DAPC and results are presented. It is seen to effectively maintain required SNR and hence read range.

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