Nash Bargaining Solution for RFID Frequency Interference

Dongyul Lee and Chaewoo Lee

We present a fair and efficient solution for selfish readers with the Nash bargaining solution (NBS) to mitigate the effects of RFID frequency interference. We compare the NBS with a solution derived by the max log-sum scheme that maximizes total utility and show that for selfish and rational readers, the NBS brings success in bargaining on resource allocation between readers unlike the max log-sum scheme, although the NBS has less total payoff compared to the max log-sum scheme.

Keywords: RFID, frequency interference, cooperative game, NBS, game theory.

I. Introduction

Frequency interference, which occurs when neighboring readers use the same or adjacent channels, reduces the efficiency of communication. Strategies such as time-division-multiplexing (TDM), frequency-division-multiplexing (FDM), or joint TDM/FDM can be adopted to alleviate the frequency interference. However, a pure FDM strategy is an impractical solution for a frequency interference problem because only a few channels are available for RFID. Hence, TDM-based solutions have been highlighted as alternatives to overcome this. However, they cannot guarantee the best strategy for the present channel condition since most of them are based on heuristic algorithm [1]. Thus, an optimization-based method, which maximizes overall payoff or obtains fair allocation, is required to solve the RFID resource allocation problem.

Resource allocation with optimization is achieved by maximizing the utility function, which is related to the payoffs of readers. Readers' payoffs are proportional to their channel occupancy time and tag detection range. Readers can either cooperate with each other or use a selfish strategy [2], [3]. If readers are selfish, to increase their payoff, they will try to fully occupy a channel. In this case, since all the readers are fully active, the tag detection range decreases and the payoff may not be the maximum value owing to frequency interference.

If readers cooperatively exchange their information, they will adjust their transmission schedule to avoid the effects of interference and to maximize the tag detection range. In this case, cooperation can lead to better results compared to non-cooperation by finding out the proper channel occupancy time.

There are several methods to allocate resources with cooperation according to goals based on efficiency or fairness. The simple optimization solutions which maximize total utility, such as a max sum or max log-sum solution, may be inappropriate as they may lead to bargaining failure between readers where some readers can acquire more payoff using a selfish strategy. This is because schemes sometimes produce fewer payoffs than are achieved by non-cooperation.

To avoid such a bargaining failure, we propose a solution to find an operating point where every reader gets at least a payoff achieved by non-cooperation using the Nash bargaining solution (NBS). The NBS is a representative solution of game theory for maximizing the product of utilities that each user achieves via cooperation relative to that achieved in non-cooperation [3]. We demonstrate that while max log-sum cannot guarantee bargaining success about resource allocation for selfish readers, our solution can do it because payoff of non-cooperation is always guaranteed to all readers although the NBS produces less total payoff compared to max log-sum.

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II. RFID Frequency Interference Model

In this section, to understand the effect of RFID frequency interference, we analyze an RFID frequency interference model consisting of a desired RFID reader, interfering readers, and tags. We explain RFID frequency interference and derive a detection range in which a desired reader can read a tag.

We assume a set of readers $\mathcal{N}=\{1,\ldots,N\}$, where each reader has a single omnidirectional antenna to communicate with tags. We further consider a single channel with an additive white Gaussian noise (AWGN) with zero mean. We do not consider tag collision for simplicity. Let x_{ti} be the tag distance of reader i to tag t. For x_{ti}, the signal received at reader i is [4]

$$S(x_{ti})=|h_{ii}|^2\, p_i \big/ x_{ti}^4, \forall i\in\mathcal{N}, \tag{1}$$

where h_{ii} is the round trip channel gain from reader i to tag t. The channel gain includes the antenna gains of reader i and tag t, and effective power reflection coefficient of tag t. The transmission power of reader i is p_i. Let P_i be the maximum power of reader i, then the individual power constraint of reader i (p_i) is given as

$$0\le p_i\le P_i, \forall i\in\mathcal{N}. \tag{2}$$

Let d_{ij} be the distance between reader i and interfering reader j, and I_i the interference signal received at reader i, then [4]

$$I_i=\sum\nolimits_{\forall j\ne i}|h_{ij}|^2\, p_j \big/ d_{ij}^2, \forall i\in\mathcal{N}, \tag{3}$$

where p_j and h_{ij} are the transmission power of interfering reader j and the channel gain of reader i from interfering reader j, respectively. Let $SINR(x_{ti}, d_{ij})$ be the signal-to-interference noise ratio at reader i for x_{ti} and d_{ij}. Then, we get

$$SINR(x_{ti},d_{ij})=\frac{S(x_{ti})}{I_i+N_i}=\frac{|h_{ii}|^2\, p_i / x_{ti}^4}{\sum\nolimits_{\forall j\ne i}|h_{ij}|^2\, p_j / d_{ij}^2+N_i}, \tag{4}$$

where N_i is noise at reader i. We assume that the received signal at reader i can be decoded only when SINR is greater than or equal to the threshold (V_{TH}), that is, [4]

$$SINR(x_{ti},d_{ij})\ge V_{\mathrm{TH}}. \tag{5}$$

Let r_i be the maximum detection range of reader i. The maximum value of x_{ti} with the maximum power P_i is r_i.

Now, we derive a utility function in our model. In general, the utility function of a reader is related to its payoff, which is proportional to the throughput in an RFID system. It depends on both the number of tags read by a reader and the channel occupancy time a reader occupies. If the tags are uniformly distributed over the network, the number of tags is directly proportional to the square of the maximum detection range. Let α_i be the channel occupancy time of reader i. A utility function u_i of reader i is defined by an arbitrary function of α_i and r_i as

$$u_i=f(\alpha_i,r_i), \forall\in\mathcal{N}. \tag{6}$$

In [5], (6) is simplified as a utility function with the product of α_i and r_i^2, which is given as

$$u_i=\alpha_i r_i^2. \tag{7}$$

For N readers, let $\boldsymbol{\alpha}=[\alpha_1,\cdots,\alpha_N]^T$ be the channel occupancy time vector of the readers, then $\boldsymbol{\alpha}$ is the chosen subject to the set

$$\mathcal{X}:=\{\boldsymbol{\alpha}\ge 0: 0\le\alpha_i\le 1, \forall i\in\mathcal{N}\}. \tag{8}$$

Even though our utility function is quite simple, it provides an abstraction of the important features of RFID resource allocation. If the vector is determined, readers are scheduled using the vector every period.

III. RFID Frequency Interference Game

In this section, an N-reader frequency interference problem in an AWGN channel with zero mean is analyzed, and we find an operating point for a fair and efficient allocation. To derive the point, we use the NBS, which maximizes the product of utilities that each user achieves via cooperation relative to that achieved in a non-cooperative game that finds strategies to maximize his/her utility without any coalitions which can be formed by the players of the game. The NBS is presented with the set of achievable utility $\mathbf{U}$ and the disagreement vector, $\mathbf{u}^c=[u_i^c,\cdots,u_N^c]^T$, which is derived by non-cooperative game.

Here, the set of achievable utilities depends on the channel occupancy time vector of the readers $\boldsymbol{\alpha}$; $\mathbf{U}=\{u_i(\alpha_i)|\alpha_i\in\boldsymbol{\alpha}\}$. That is, the TDM strategy, which provides readers with authority to occupy a channel at different time, will be adopted by readers via cooperation. From (5), then, the maximum detection range r_i of reader i on cooperative game is given as

$$r_i=\left(\frac{|h_{ii}|^2 P_i}{V_{\mathrm{TH}} N_i}\right)^{1/4}, \forall i\in\mathcal{N}. \tag{9}$$

Hence, when α_i is given, the utility u_i of the reader i on a cooperative game becomes

$$u_i(\alpha_i)=\alpha_i r_i^2, \forall i\in\mathcal{N} \tag{10}$$

with a constraint as in (8). The disagreement vector in our model is achieved when every reader tries to occupy a channel with its maximum power for full time because the selfish readers prefer it without any communications. From (5), the maximum detection range r_i^c of reader i on non-cooperative game is given as

$$r_i^c=\left(\frac{|h_{ii}|^2 P_i}{V_{\mathrm{TH}}\left(\sum\nolimits_{\forall j\ne i}|h_{ij}|^2\right)P_j / d_{ij}^2+N_i}\right)^{1/4}, \forall i\in\mathcal{N}. \tag{11}$$

Since the channel occupancy time of all readers is 1, the utility u_i^c for reader i on a non-cooperative game is given as

$$u_i^c = (r_i^c)^2, \forall i \in \mathcal{N}. \quad (12)$$

Rational readers will want to use the TDM strategy as long as

$$\mathbf{U} \geq \mathbf{u}^c, \quad (13)$$

$$\sum_{\forall i \in \mathcal{N}} \alpha_i \leq 1. \quad (14)$$

NBS is a bargaining agreement for maximizing the product of utility that a cooperative game achieves relative to that achieved in a non-cooperative game with the interesting axioms [3].

If **U** is convex, the NBS is unique under constraints (13) and (14), which is obtained by

$$\mathbf{s}^* = \arg \max_{u_i(\alpha_i) \in \mathbf{U}} \prod_{i=1}^{N} (u_i(\alpha_i) - u_i^c). \quad (15)$$

Now, we find the condition where the NBS is unique in our model and then obtain the solution. To easily find it, from (10), we rewrite (12) on a non-cooperative game as

$$u_i^c = r_i^2 \Big/ \left(\sum\nolimits_{\forall j \neq i} \beta_{ij} SNR_j + 1 \right)^{1/2}, \forall i \in \mathcal{N}, \quad (16)$$

where $SNR_j = \dfrac{|h_{jj}|^2 P_j}{N_i r_j^2}$ and $\beta_{ij} = \dfrac{|h_{ij}|^2 / d_{ij}^2}{|h_{jj}|^2 / r_j^2}$. Now, we find the existence condition for the NBS in a frequency interference game with N readers.

Definition 1. We define $f(x)$ as

$$f(x) = \min \left\{ y : y = 1 \big/ (x+1)^{1/2} \right\}. \quad (17)$$

Claim 1.

1. For all $x \in \mathbb{R}^+$, $0 < f(x) < 1$.
2. $f(x)$ is a monotonic decreasing function.

Proof. For $x \in \mathbb{R}^+$, let $g(x, \gamma)$ be defined by

$$g(x, \gamma) = \gamma - 1 \big/ (x+1)^{1/2}. \quad (18)$$

For $x > 0$, $g(x, \gamma)$ satisfies (1) if $\gamma = 1$, $g(x, 1) \geq 0$; and (2) if $\gamma = 0$, $g(x, 0) \leq 0$ in x. γ satisfying $g(x, \gamma) = 0$ for $x \in \mathbb{R}^+$ always exists between 0 and 1 according to the intermediate value theorem since $g(x, \gamma)$ is an increasing function in γ for fixed x. To maintain $g(x, \gamma) = 0$, we need to decrease γ when x increases.

Hence, we can get the condition where readers want to choose a cooperative strategy rather than a selfish strategy using the characteristics of $f(x)$. □

Lemma 1. Let α_i^m be the minimum channel occupancy time of reader i; to be guaranteed to obtain the payoff of a cooperative game equal to that of a non-cooperative game. Then, we can get

$$\alpha_i^m = f\left(\sum_{\forall j \neq i} \beta_{ij} SNR_j \right). \quad (19)$$

Proof. Since $\alpha_i^m = \alpha_i$ when $u_i = u_i^c$, from (10) and (16), α_i^m is given by

$$\alpha_i^m = 1 \Big/ \left(\sum\nolimits_{\forall j \neq i} \beta_{ij} SNR_j + 1 \right)^{1/2} \quad \forall i \in \mathcal{N}. \quad (20)$$

□

Theorem 1. The NBS exists if the following inequality holds.

$$\sum_{\forall i \in \mathcal{N}} \alpha_i^m = \sum_{\forall i \in \mathcal{N}} f\left(\sum_{\forall j \neq i} \beta_{ij} SNR_j \right) \leq 1 \quad (21)$$

Proof. Bargaining between all readers will succeed if all readers are assigned resource greater than α_i^m. □

The optimal problem to obtain the NBS can be formulated as

$$\arg \max_{\alpha} \prod_{i=1}^{N} (u_i(\alpha_i) - u_i^c) \quad (22)$$

with the constraints (8), (13), and (14). The primal problem (22) is convex because of theorem 1 and claim 1. Therefore, (22) has no duality gap, and so we solve it via a dual formulation. We associate dual variables $\boldsymbol{\lambda} = (\lambda_i)_{i \in \mathcal{N}}$ with a constraint (8), $\boldsymbol{\mu} = (\mu_i)_{i \in \mathcal{N}}$ with a constraint (13), and σ with a constraint (14), resulting in the Lagrangian.

$$L(\boldsymbol{\lambda}, \boldsymbol{\mu}, \sigma, \boldsymbol{\alpha}) := \log \sum_{\forall i \in \mathcal{N}} (u_i(\alpha_i) - u_i^c)$$

$$+ \sum_{\forall i \in \mathcal{N}} \lambda_i \alpha_i + \sum_{\forall i \in \mathcal{N}} \mu_i (u_i(\alpha_i) - u_i^c) + \sigma \left(1 - \sum_{\forall i \in \mathcal{N}} \alpha_i \right). \quad (23)$$

Thus, an optimal solution to the primal problem is given by

$$\min_{\sigma \geq (\boldsymbol{\lambda}, \boldsymbol{\mu}) \geq 0} \max_{\boldsymbol{\alpha} \in \mathcal{X}} L(\boldsymbol{\lambda}, \boldsymbol{\mu}, \sigma, \boldsymbol{\alpha}). \quad (24)$$

From Karush-Kuhn-Tucker conditions for the problem, by taking the derivative with respect to the variable α_i and comparing the result to zero, we get

$$\frac{r_i^2}{u_i(\alpha_i) - u_i^c} = -\lambda_i - \mu_i r_i^2 + \sigma \quad (25)$$

with the constraints (8), (13), and (14).

We have λ_i, $\mu_i = 0$, $\forall_i \in \mathcal{N}$ if (21) is always satisfied. By taking the derivative with respect to α_i and comparing the result to zero, the NBS for reader i can easily be obtained as

$$\alpha_i^* = \frac{1}{N} - \frac{1}{N} \sum_{j=1}^{N} (r_j^c / r_j)^2 + \left(\frac{r_i^c}{r_i} \right)^2 \quad (26)$$

with the constraint of (21). For fixed N readers,

$\mathbf{s}^* = [\alpha_1^*, \alpha_2^*, \cdots, \alpha_N^*]^T$ becomes the NBS. Schemes to obtain the NBS and readers in MAC layer are required to exchange the maximum detection ranges on a cooperative game and on a non-cooperative game. To observe the characteristics of NBS, in this letter, we calculate the NBS based on the centralized method only under the assumption that every reader knows the information of other readers before each reader transmits its data. We also schedule readers randomly without any scheduling algorithms because (26) leads to same results regardless of the scheduling order of readers.

IV. Results

In this section, we find the NBS in a five-reader interference model having flat fading and AWGN with zero mean and variance 10^{-5}. We also compare the NBS with a max log-sum scheme, which is one of the solutions to maximize the total utility. We consider two network scenarios as shown in Fig. 1. Readers, represented as small circles in the figure, are randomly distributed in each scenario, and numbers written near the circles are used to distinguish the readers. We assume that every reader transmits its data with a maximum power of 30 dBm and that the threshold (V_{TH}) or target SNR is 11.8 dB [4]. We also assume that the channel gains from a reader to a tag and from a reader to a reader are the same, which provides all readers with the same tag detection range without interference. Under these conditions, we can easily compare the NBS with the max log scheme because the max log scheme assigns every reader the same time as 1/5.

Table 1 shows the channel occupancy time vectors and the utility vectors of the readers in terms of the NBS in network scenarios 1 and 2. The table also provides the minimum channel occupancy time vectors (MCOT) which guarantee that the utility of a cooperative game equals that of a non-cooperative game in the two network scenarios. Although, in terms of log sum of the utility, the max log-sum scheme has higher utility compared to the NBS, we can observe that the solution of the max log-sum scheme has lower utility than that of MCOT for reader 5 in scenario 1 and readers 1 and 3 in scenario 2. This means that for selfish readers, while the NBS succeeds in reaching an agreement of bargaining, the max log-sum scheme can fail in resource bargaining. This is because, compared to the max log-sum scheme, some readers can achieve higher utility using a selfish strategy.

In conclusion, our solution based on game theory is useful to understand the way readers divide resources in an RFID network, leading to bargaining success. Our result can be applied to other distributed environments like an RFID network where all users are selfish and rational. Our solution has two limitations: i) it has to be changed into a distributed algorithm to be applied in practical circumstances; however, it is easily developed by exchanging channel information between readers, and ii) it does not allow some of the readers to simply create a coalition when bargaining fails, which means that readers can only increase their payoff by cooperating with one another. In future, we will continue the remaining works to develop a practical scheme in an RFID network.

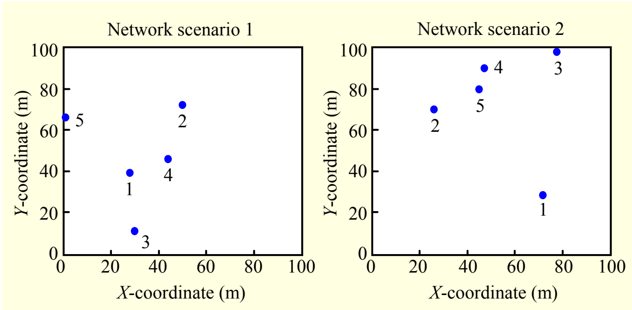

Fig. 1. Geometric plot of two network scenarios.

Table 1. Resource allocation for two network scenarios.

Reader number	Network scenario 1			Network scenario 2		
	NBS (α_i)	MCOT (α_i^m)	Utility (u_i)	NBS (α_i)	MCOT (α_i^m)	Utility (u_i)
Reader 1	0.154	0.129	103	0.334	0.305	223
Reader 2	0.214	0.189	143	0.188	0.158	125
Reader 3	0.222	0.197	148	0.240	0.210	160
Reader 4	0.155	0.130	103	0.121	0.091	80
Reader 5	0.254	0.229	170	0.117	0.088	78
$\log \sum_{i=1}^{5} u_i$			6.5028			6.5013

*Log-sum of utility of max log-sum scheme is 6.5035.

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