Anarchy vs. Cooperation on Internet of Molecular Things

Caglar Koca, *Student Member, IEEE,* Ozgur B. Akan, *Fellow, IEEE*

***Abstract*—Using the advances in molecular communications, nanomachines as a group can undertake complex tasks. With the emergence of Internet of Molecular Things (IoMT), such nanomachine groups are now larger than ever. However, the minimal design of nanomachines makes cooperation difficult. In this paper, we investigate the performances of anarchic and cooperative transmitters in IoMT. We design a molecular communication game in which nanomachines choose to cooperate or confront. We discuss the advantages and disadvantages of cooperation and state the possible transmitter personalities using game theoretic principles. Moreover, we focus on methods to ensure cooperation and we explore the optimal transmitter behaviour if its partner rejects cooperation. Finally, we deduce that although ensuring cooperation may be done effectively with minimum hardware, anarchy is not necessarily a bad result. We also realize that in case a transmitter rejects cooperation, perpetual confrontation is not a good approach.**

***Index Terms*—Game Theory, Nash Equilibrium, Cooperative Game**

I. Introduction

Molecular communication (MC) is one of the fast developing paradigms in nanocommunications [1]. Inspired by communications in nature, MC offers bio-compatible solutions to nanocommunication systems [2]. Hence, tasks may be divided between cooperating nanodevices, which communicate via molecular communication networks (MCN) [3]. The novel concept of Internet of Molecular Things (IoMT) brings even larger groups of nanomachines collaborating to achieve more complex tasks [4].

MC requires four elements: Transmitter, receiver, transmission medium and information carrier. As the name suggests, information carriers are molecules. In the early works, information carriers were always assumed to move via diffusion [5, 6]. However, lately, active transport is used as well in modeling MCNs [7].

There exist several nature-inspired MC schemes modeled and examined. These schemes include short range communication by gap-junction channels [9], medium range communication by flagellated bacteria and catalytic nanomotors and longer range communication using pheromones, spores and pollen [8, 10]. As we can see, nature inspired MC offer a wide range of applications.

Authors are with the Next-generation and Wireless Communications Laboratory (NWCL), Department of Electrical and Electronics Engineering, Koc University, Istanbul, Turkey (e-mail: {cagkoca, akan}@ku.edu.tr).

Ozgur B. Akan is also with Internet of Everything (IoE) Group, Electrical Engineering Division, Department of Engineering, University of Cambridge, CB3 0FA Cambridge, UK (e-mail: oba21@cam.ac.uk).

This work was supported in part by the ERC project MINERVA (ERC-2013-CoG #616922), and the EU project CIRCLE (EU-H2020-FET-Open #665564).

The primary advantages of nature-inspired MC are their feasibility for intrabody systems and their robustness. Natural MC systems have evolved over three billion years and adapted to even most inhospitable conditions [11], [12]. The extraordinary success of evolution of natural MC systems may be studied with game theory [13–15]. Due to the innate advantages of the use of game theory in understanding of the evolution of living bodies, we too can employ the tools of evolutionary game theory and apply them for IoMT. In fact, due to the size of the molecular networks in IoMT, analytical solutions may be hard, even impossible. Hence, use of principles of game theory to understand communication and cooperation for IoMT is inevitable.

In the current literature, the only work that uses game theory in MC is [16]. In [16], the authors use basic principles of game theory, such as Nash Equilibrium and Nash Bargaining to discuss the relations between two transmitters. However, to the best of our knowledge, there exists no work that uses evolutionary game theory tools to explore transmitter behaviours and cooperation methods in an MCN or IoMT.

Our objective in this paper is to study the cooperation methods and performance differences between MCNs without any cooperation between its transmitting nodes (TNs) and MCNs with cooperating TNs. We analyze cooperating and confronting TNs in uniterated and iterated scenarios. We focus on the evaluation of *aggressive, submissive, cooperating, reconciliating* and *forgiving* TN performances and the cost of ensuring cooperation. Depending on the cost of cooperation, nanomachine design may change to alleviate or forsake the chance of cooperation. Moreover, if the TNs may choose cooperation or anarchy depending on the other TNs in the network.

The rest of this paper is organized as follows: In Section II, we present our system model. In Section III, we illustrate uniterated two transmitters game. In Section IV, we develop the iterated two transmitters game. In Section V, we move to uncooperating transmitters. Section VI presents the simulation results and Section VII is the conclusion.

II. System Model

As any molecular communications network (MCN), our system consists of an information carrier, transmitting nodes (TNs), transmission medium and receiving nodes (RNs). We assume that MCN is confined in a large environment with absorbing boundaries. We describe the details of our system model as follows.

A. Information Carrier

Information carrier in molecular communications is a molecule able to diffuse and propagate in a medium. The diffusion of the molecules obeys the Brownian motion. These molecules are indistinguishable and do not interact with each other.

B. Transmitting Nodes

The TNs in the MCN are parts of larger nanomachines fulfilling communication duties with either other nanomachines are nano to macro gateways. Depending on the duties of the nanomachine, TNs may be triggered to relay sensory information, task reports or simple "I am alive." signals. If triggered, TNs have the ability to independently release molecules from their reserve pool. All TNs use the same molecule as the information carrier. TNs may decide on the amount of molecules they release to the system. TNs are able to sense their immediate vicinity, i.e., the number of molecules on their surface. In fact, this amount is a part of their gaming strategy. We assume TNs have a large enough pool for enough iterations. TNs may be aware of the position of the receiving nodes with respect to their position, but they are not aware of the position of other TNs.

C. Transmission Medium

Transmission medium may be any medium allowing molecules to diffuse. Without loss of generality, in order to reduce the mathematical burden, we assume the medium is homogeneous and isotropic, i.e., the diffusivity of the molecules does not depend on the position or direction of the medium. The medium is two-dimensional. The height of the medium is minimal and ignored in the calculations. The concentration of the information carrying molecule in the medium is never zero. It drops to some threshold C_{th} and remains constant.

D. Receiving Nodes

Without loss of generality, we assume there is only one receiving node (RN) in the MCN. RNs do not distinguish TNs. RN receives a 1, if the concentration of molecules produced by a TN at position of RN at time t, $C_{RN}(t)$, increases more than the saturation ratio, α from time t to time $t + \Delta T$. However, if the increase ratio is less than α, rather than rejecting it altogether, RN receives 1 with a probability proportional to the increment ratio. In this way, RN minimizes the risk of receiving accidental 1's. Hence, RN behaviour is summarized as

$$p_1(t) = \begin{cases} 1, & \frac{\max\limits_{t \to t+\Delta T} C_{RN}}{C_{RN}(t)} \geq \alpha \\ 0, & \frac{\max\limits_{t \to t+\Delta T} C_{RN}}{C_{RN}(t)} \leq 0 \\ \frac{\max\limits_{t \to t+\Delta T} C_{RN}}{\alpha C_{RN}(t)}, & 0 \leq \frac{\max\limits_{t \to t+\Delta T} C_{RN}}{C_{RN}(t)} \leq \alpha \end{cases} \tag{1}$$

where $P_1(t)$ is the probability of 1 of that particular RN. Fig 1 shows the RN behaviour with respect to the concentration ratio.

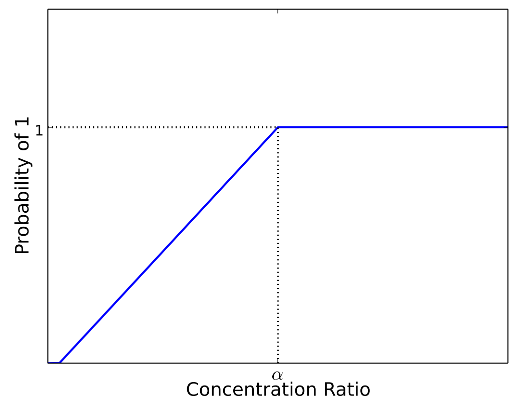


Fig. 1. RN Behaviour vs Concentration Ratio. Note that if concentration ratio exceeds a certain threshold, α, RN saturates.

E. Payoff

All games must have a payoff, i.e., the motivation of players or the quantity which they aim to maximize. In this communication scenario, the payoff is the success rate of transmitting a correct 1, i.e., p_i. Therefore, all TNs try to maximize their p^is. If the game is repeated N times, the payoff is $\sum_{i=1}^{N} p^i$, where p^i is the P_1 at the i^{th} try.

If the TNs cooperate, their objective is to maximize the total p^i in the system, rather than maximizing individual p^is.

III. Uniterated Two Transmitters Game

Here, we calculate the best response of a transmitting node in an MCN consisting of two transmitting nodes and one receiving node. We first start with the most trivial game, and then move to more complex games.

In this game, two TNs emit signal for once. TNs employ well-defined time slots for their emission. Although TNs do not know the order of emission, they are aware of the molecular concentration in their vicinity. Hence, at the time of emission, they can very accurately assess whether the other TN has used the channel recently. Depending on this assessment, TNs can employ one of the two strategies:

- C_1: Release half of the reserve pool
- C_2: Release all of the reserve pool

Furthermore, this game is uniterated, i.e., TNs cannot retaliate due to the unfavourable decisions of the other TN. The payoffs of this game is their respective probability of 1's, p^i. Note that in this communication scheme, $p^i = (1 - BER)$. Using the TN model developed in Section II, for the first TN, we find p^1 as

$$p^1 = \begin{cases} 1, & \max\limits_{t: t_1 \to t_1+\Delta T} \frac{C_{RN}^1(t)+C_{eq}}{C_{eq}} > \alpha \\ 0, & \max\limits_{t: t_1 \to t_1+\Delta T} \frac{C_{RN}^1(t)+C_{eq}}{C_{eq}} \leq 1 \\ \frac{C_{RN}^1(t)+C_{eq}}{\alpha C_{eq}}, & 0 < \max\limits_{t: t_1 \to t_1+\Delta T} \frac{C_{RN}^1(t)+C_{eq}}{C_{eq}} < \alpha \end{cases} \tag{2}$$

where $C^1_{RN}(t)$ denotes the concentration at the position of RN due to TN$_1$ at time t, t_1 is the time at which TN$_1$ released its molecules, ΔT is the RN property until which an increase ratio is determined by RN, C_{eq} is the equilibrium concentration of the carrier molecule and α is the minimum concentration ratio of the RN such that $p^i = 1$, i.e., the receiver is saturated. We also know that carrier molecule obeys the 2D Brownian motion model, hence, C^1_{RN} can be calculated as

$$C^1_{RN}(t) = \frac{A_1}{4\pi Dt} e^{-\frac{r_1^2}{4Dt}} \tag{3}$$

Here, A_1 is the number of molecules released by TN$_1$, r_1 is the distance between TN$_1$ and RN, and D is the diffusivity of the carrier molecule.

In order to calculate p^2, we first need to define maximum concentration ratio, CR_{max} as

$$CR_{max} = \max_{t',t'':t_2 \to t_2+\Delta T} \frac{C^2_{RN}(t') + C^1_{RN}(t') + C_{eq}}{C^2_{RN}(t'') + C^1_{RN}(t'') + C_{eq}} \tag{4}$$

where $t' = \arg\max\{C^2_{RN}(t) + C^1_{RN}(t) + C_{eq}\}$, and $t'' = \arg\min\{C^2_{RN}(t) + C^1_{RN}(t) + C_{eq}\}$ for $t_2 \leq (t', t'') \leq t_2 + \Delta T$. Now, we can express p^2 as

$$p^2 = \begin{cases} 1, & CR_{max} > \alpha \\ 0, & CR_{max} \leq 1 \\ \frac{CR_{max}}{\alpha}, & 1 \leq CR_{max} \leq \alpha \end{cases} \tag{5}$$

Similarly,

$$C^2_{RN}(t) = \frac{A_2}{4\pi Dt} e^{-\frac{r_2^2}{4Dt}} \tag{6}$$

TNs have the ability to choose A_i, either as $\frac{A}{2}$ or A, where A is the total number of molecules in the pool. TNs perform this choice with the information they receive by sensing the concentration in their immediate vicinity.

Here, we choose as $\Delta T = \frac{r^2}{4D}$ to ensure that the molecule concentration around the RN reaches its maximum value within ΔT seconds due to a TN r distance away from RN. Using ΔT as stated, we observe that

$$\max_{t_i \to t_i+\Delta T} C^i_{RN} = C^i_{RN}(t_i + \Delta T) \tag{7}$$

hence, we can relax the max expressions in (2).

For the sake of simplicity, we choose $t_2 - t_1 = \Delta t = \Delta T$. Note that the choices of either Δt or ΔT are completely arbitrary and only affect the payoffs. Furthermore, note that although payoffs may change the actions taken by the TNs, they cannot affect their decision making process.

Thus, we now calculate p^1 as follows.

$$p^1 = \begin{cases} 1, & \frac{A_1 + C_{eq}}{\pi e C_{eq} \Delta T} > \alpha \\ \frac{A_1 + C_{eq}}{\alpha \pi e C_{eq} \Delta T}, & \frac{A_1 + C_{eq}}{\pi e C_{eq} \Delta T} < \alpha \end{cases} \tag{8}$$

Calculating p^2 is not trivial. However, t' and t'' only depend on the ratios of $\frac{A_2}{A_1}$ and $\frac{A_1}{C_{eq}}$.

Regardless of $\frac{A_2}{A_1}$ and $\frac{A_1}{C_{eq}}$, the matrix form of this game is given in Table I, where $p^i_{C_1C_2}$ is probability of 1 for TN$_i$ if TN$_1$ chooses C_1 and TN$_2$ chooses C_2, such that $C_1, C_2 \in \{\frac{A}{2}, A\}$.

TABLE I
PAYOFF MATRIX FOR A GENERIC TWO NODE TRANSMISSION GAME

		TN$_2$: A/2		TN$_2$: A	
TN$_1$	A/2	$p^1_{\frac{A}{2}\frac{A}{2}}$	$p^2_{\frac{A}{2}\frac{A}{2}}$	$p^1_{\frac{A}{2}A}$	$p^2_{\frac{A}{2}A}$
	A	$p^1_{\frac{A}{2}A}$	$p^2_{\frac{A}{2}A}$	p^1_{AA}	p^2_{AA}

A. Cooperating Transmitters

We know that in case of cooperation, the transmitters try to maximize their total probability of 1, i.e., $\max \sum_{i=1}^{N} p^i$. Hence, cooperating transmitters may achieve a success rate of p_C, which can be calculated as

$$p_C = \max_{C_1, C_2 \in \{A, {}^{A}/_{2}\}} \left\{ p^1_{C_1C_2} + p^2_{C_1C_2} \right\} \tag{9}$$

We know that regardless of C_2, $p^1_{AC_2} \geq p^1_{\frac{A}{2}C_2}$. Similarly, regardless of C_1, $p^2_{C_1A} \geq p^2_{C_1\frac{A}{2}}$. Furthermore, due to the order of emission, p^1 is not affected by C_2. Using these results, we immediately realize that p_C cannot be achieved for $C_1C_2 = \frac{A}{2}\frac{A}{2}$ and $C_1C_2 : A\frac{A}{2}$. The remaining combinations suggest that p_C can be achieved either for $C_1C_2 = \frac{A}{2}A$, or $C_1C_2 = AA$. Hence

$$p_C = \max\left(\frac{1}{2}\left(p^1_{\frac{A}{2}A} + p^2_{\frac{A}{2}A}\right), \frac{1}{2}\left(p^1_{AA} + p^2_{AA}\right) \right) \tag{10}$$

(10) implies that if TN$_1$ choosing A benefits itself more than the damage it causes to TN$_2$, it must choose A, otherwise, it must resort to $\frac{A}{2}$.

B. Anarchic Transmitters

We see that cooperating transmitters try to maximize the overall probability of 1. In order to maximize their total probability of 1, TN$_1$ may need to favour a more egalitarian approach. However, anarchic transmitters do not have egalitarian principles. Hence they ignore the overall probability of 1. Instead, they only aim to maximize their own probability of 1.

We note that since there is an order in our communication scheme, TN$_1$ does not need to consider TN$_2$. Any action of TN$_2$ does not affect p^1 in any way. Hence, TN$_1$ chooses A. Since both transmitters are selfish, TN$_2$ is aware that TN$_1$ chooses the action that maximizes its own probability of 1. We can express p_A, the total probability of 1 for an anarchic system as

$$p_A = \frac{1}{2}\left(\max_{C_1 \in \{A, {}^{A}/_{2}\}} p^1_{C_1C_2} + \max_{C_2 \in \{A, {}^{A}/_{2}\}} p^2_{(\arg\max p_1)C_2} \right) \tag{11}$$

where $\arg\max p_1$ is the C_1 that maximizes p^1.

Using the results in Table I, we express p_A such as

$$p_A = \frac{1}{2}\left(p^1_{AA} + p^2_{AA}\right), \tag{12}$$

which is also the Nash Equilibrium for this system. Using p_C and p_A, we express the price of anarchy, PoA as

$$PoA = p_C - p_A \tag{13}$$

Note that PoA is zero if the choice of TN_1 that maximizes its own probability of 1 also maximizes the total probability of 1, i.e., $\arg\max p^1 = \arg\max \left(p^1 + p^2\right)$.

IV. Cooperation in iterated two transmitters game

In the previous section, we calculated the outputs of cooperating and anarchic transmitters in a game, in which both transmitters emitted consecutively but only once. In this game, two TNs similarly emit signal consecutively but for many times. The well-defined time slots are still present, however, between two cycles of the game, enough time passes such that the concentration of the carrier molecule drops back to its equilibrium value. The transmitters do not know the order of emission, and the order of emission may change at each cycle.

The defining difference of this game is that transmitters may retaliate in a future cycle if the other transmitter does not adopt an egalitarian stance. Table I gives the payoffs for a single iteration of this game.

In this case the *personalities* of the transmitters determine the aggregate payoffs in N iteration of this game. Possible personalities can be listed as follows:

- **Submissive:** Submissive TNs, as the first emitter, always choose $\frac{A}{2}$ in all iterations regardless of the behaviour of their opponent.
- **Aggressive:** Aggressive TNs choose A in all iterations regardless of the behaviour of their opponent.
- **Cooperative:** Cooperative TNs try to establish a coordinated effort to maximize the aggregate payoffs of themselves and the overall system.

Here, we assume that both TNs are cooperative. We investigate methods to ensure cooperation on the face of misunderstandings or accidental aggressions. We first consider a basic payback mechanism, and then, introduce reconciliation and forgiveness.

A. Cooperation with Payback

Cooperative TNs may employ payback tactics to ensure cooperation. Such tactics are:

- **Tit for tat:** The TN acts cooperative, until the first aggression of the other TN.
- **Tit for double tat:** The TN acts cooperative, until the second aggression of the other TN.
- **Tit for N tat:** The TN acts cooperative, until the N^{th} aggression of the other TN.

The main point of all payback tactics is to threaten the non-cooperating entity with reduced payoff. A TN trying to achieve cooperation may even make concessions from its own payoff to force the other TN to cooperate.

Now, we introduce misunderstood aggressions, i.e., even if a TN is not selfish, there is a chance that its actions are misunderstood by the other TN. Assuming that the misunderstanding probability is for each iteration is β, probability of the MCN fall into an unwanted confrontation at the i^{th} iteration can be calculated as

$$p_{conf}(i) = \binom{i-1}{N-1}\beta^N(1-\beta)^{i-N} \tag{14}$$

It is obvious that as i increases, an unwanted confrontation is inevitable. Using the parameters in Table I, we can calculate the expected aggregate payoff of two cooperating TNs with a misunderstanding probability β, i.e.,

$$P_{agg} = \sum_{i=N}^{m} p_{conf}(i)\{(i-N)(p^1_{\frac{A}{2}A} + p^2_{\frac{A}{2}A}) + (m-i+N)(p^1_{AA} + p^2_{AA})\} \tag{15}$$

Using (10) and (12) and assuming that $p_C \neq p_A$,

$$P_{agg} = \sum_{i=N}^{m} p_{conf}(i)\{(i-N)p_C + (m-i)p_A\} + Np_C \tag{16}$$

Note that, in (15) and (16), we assume that the tit for N tat threshold is exceeded. The probability of not reaching the threshold, i.e., the probability of no confrontation is

$$p_{no-conf}(m) = 1 - p_{conf}(m) = \sum_{i=0}^{N-1}\binom{m}{i}\beta^i(1-\beta)^{m-i} \tag{17}$$

With a simple ratio test, we can show that for large m, $p_{no-conf}$ approaches 0. Hence, a confrontation is inevitable if the game is to be iterated for many cycles.

B. Cooperation with Reconciliating Transmitters

We observe that even if the TNs are willing to cooperate, tit for N tat has a possibility to spiral into an unwanted confrontation between TNs. Although that possibility decreases as N increases, it has no escape strategy from confrontation. Reconciliation provides an escape strategy from an unwanted confrontation by two parties.

- **Reconciliating:** The TN tries to initiate cooperation with a certain probability, even if the other TN acts aggressively.

We define the reconciliation constant, γ, of a TN as the probability of reconciliation attempt after confrontation starts. We realize that if the confrontation starts at the i^{th} iteration, the aggregate throughput for the rest of the transmission is

$$P'_{agg} = (m-i)p_A \tag{18}$$

where P'_{agg} is the aggregate payoff for both TNs after the confrontation.

However, if one of the TNs is reconciliating, the aggregate throughput after the confrontation jumps to cooperation with a probability of $\gamma(1-\beta)$. Here, $(1-\beta)$ term stands for the other TN not misunderstanding this reconciliation attempt. Therefore,

$$P'_{agg} = \sum_{j=1}^{m-i} j\big(1-\gamma(1-\beta)\big)p_A + \gamma(1-\beta)(m-i-j)p_C \tag{19}$$

Note that the second part of (19) is the improvement over (18), and for $\gamma = 0$, (19) collapses into (18).

We now depict this system as a state machine with two states: Cooperation and confrontation. The transition probability from cooperation to confrontation is given in (14). Note that $p_{conf}(i)$ changes with i, which now stands for the number of iterations after each reconciliation. The state machine representation of such a system is presented in Fig. 2.

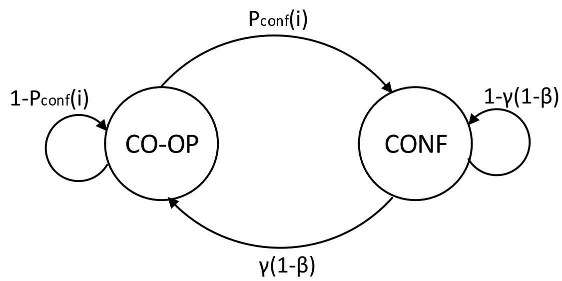


Fig. 2. State machine representation of reconciliating TNs.

Since the probability of misunderstanding is β, on average, in $\frac{1}{\beta}$ trials a misunderstandings occurs and on average in $N\frac{1}{\beta}$ iterations cooperation turns into confrontation. Similarly, in $\frac{1}{\gamma(1-\beta)}$ iterations, the confrontation resolves into cooperation. Hence, in such a system the average payoff is

$$P_{agg} = \frac{N\frac{1}{\beta}p_C + \frac{1}{\gamma(1-\beta)}p_A}{N\frac{1}{\beta} + \frac{1}{\gamma(1-\beta)}} \tag{20}$$

C. Cooperation with Forgiving Transmitters

Reconciliation is an effective way to deviate from unnecessary confrontation. However, reconciliation can only be achieved if the TNs confront each other. We propose forgiveness to prevent confrontation altogether

- **Forgiving:** TNs employing tit for N tat, forgive one aggression, if a number of successive iterations of cooperation, M, occurs.

The state machine representation for an MCN with misunderstanding rate of β and required number of successive iterations of cooperation of S is presented in Fig. 3.

As we can see in Fig. 3, we now have intermediate states, which represent the aggressions, as well as the cooperation and confrontation states. In fact, these intermediate states has M intermediate state of theirs as well. Transition probability from a lower aggression state to higher aggression state is equal to the misunderstanding probability, β. The transition probability from a higher aggression state to a lower aggression state, i.e., probability of forgiving, is $(1-\beta)^M$. Finally the probability of no state change is $\Delta = 1 - \beta - (1-\beta)^M$ for intermediate states, $1-\beta$ for the cooperation state and $(1-\beta)^M$ for the confrontation state.

In order for such an MCN not to sprint into a confrontation, we need to choose M at least $\beta = (1-\beta)^M$. Thus

$$M \leq \frac{\log \beta}{\log(1-\beta)} \tag{21}$$

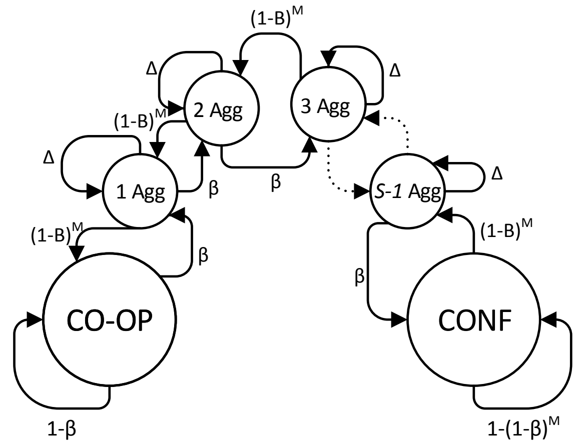


Fig. 3. State machine representation of forgiving TNs.

With such M and S, the state transition probabilities need to satisfy

$$P_{COOP} = (1-\beta)P_{COOP} + (1-\beta)^M P_1 \tag{22}$$
$$P_1 = \beta P_{COOP} + \Delta P_1 + (1-\beta)^M P_2 \tag{23}$$
$$P_2 = \beta P_1 + \Delta P_2 + (1-\beta)^M P_3 \tag{24}$$
$$\vdots$$
$$P_{S-1} = \beta P_{S-2} + \Delta P_{S-1} + (1-\beta)^M P_{CONF} \tag{25}$$
$$P_{CONF} = (1-(1-\beta)^M)P_{CONF} + \beta P_{S-1} \tag{26}$$

Choosing M as in (21), using (22), we realize that $P_{COOP} = P_1$. Further analysis reveals that all states have the same probability, i.e., the probability of the system being in any state is

$$P_i = \frac{1}{S+1}, i \in \{COOP, 1, 2 \ldots S-1, CONF\} \tag{27}$$

If M is chosen to be smaller than $\frac{\log \beta}{\log 1-\beta}$, the system shifts to cooperation, i.e., the state probabilities grow as they approach cooperation. Similarly, if we choose M to be greater than $\frac{\log \beta}{\log 1-\beta}$, the system moves to confrontation.

Solving (22)-(26), we realize that the system is in confrontation with probability $\left(\frac{\beta}{1-\beta^M}\right)^{S+1}$. Hence, the payoff per iteration is

$$P_{agg} = \left(\frac{\beta}{1-\beta^M}\right)^{S+1} p_A + \left(\frac{\beta}{1-\beta^M}\right)^{S+1} p_C \tag{28}$$

D. The cost of cooperation

In game theory, the cost (or price) of anarchy refers to the degradation of system due to the selfish behaviours of the players. The main reason of such an approach is due to the fact that cooperation and decision making in most systems do not carry a cost. However, MCNs are formed with nanomachines with tight energy consumption restrictions. Both due to the size and energy policy, TNs are equipped with the minimum hardware to accomplish their goals. Hence, achieving cooperation may require extra hardware which may not be suitable for nanomachines.

We investigate the cost of cooperation in three different categories; namely sensory, memory and decision making.

1) Cost of Sensory Equipment: In order to achieve cooperation, it is essential for the TNs to sense the carrier molecule concentration in the channel. Hence, the TNs might not need a channel sensing equipment if they choose anarchy over cooperation. However, such an equipment may still be useful even if cooperation is not desired, i.e., TN may use it to economise the total number of carrier molecules in its pool.

2) Cost of Memory: To ensure cooperation with payback, if tit for N tat is desired, $\log_2 N$ latches is needed. If TNs decide to employ cooperation with forgiving approach, they further need an additional counter with $\log_2 M$ latches to count the successive cooperations. The utilization of such an equipment may be costly for a nanomachine.

3) Cost of Decision Making: TNs still needs extra logic circuits to use the sensory data and data stored in the counters to decide on the amount of carrier molecules they emit. The size of the circuit grows with N and M. TN may be more energy efficient without these additional circuitry.

We realize that cooperation in MCNs may be costly. Hence, in some cases, anarchy might be a better alternative over cooperation.

V. Handling Transmitters Refusing Cooperation

In the previous section, we discussed anarchic vs. cooperative transmitters in an iterated two transmitters game. We state that a TN may employ a payback mechanism i.e., tit for N tat to ensure cooperation. In this section, we move one step further: *How to handle if the other TN blatantly refuses cooperation?*

We know that payback mechanisms are to ensure cooperation. However, if the other TN is close to dialogue, any cooperation attempt certainly fails. In such cases, both in order to ensure fairness and to increase its payoff, TNs might make the payback mechanism permanent. The choice of anarchy in an MCN, equalizes the payoffs of both TNs by reducing the payoff of the non-cooperating TN and increasing the payoff of the TN that tried to cooperate. In anarchy, individual payoffs per iteration for the TN trying to establish cooperation, p^{coop} and for the TN happy with anarchy, p^{conf} become

$$p^{coop} = p^{conf} = p_A. \tag{29}$$

Hence, the aggregate payoff of such a system for each iteration is

$$P_{agg} = 2p_A. \tag{30}$$

However, if cooperating TN decides to give up on the payback mechanisms, i.e., if it continues to cooperate even if the other TN acts aggressively, the individual and aggregate payoffs become

$$p^{coop} = \frac{1}{2}\left(p^1_{\frac{A}{2}A} + p^2_{AA}\right), \tag{31}$$

$$p^{conf} = \frac{1}{2}\left(p^1_{AA} + p^2_{\frac{A}{2}A}\right), \tag{32}$$

$$P_{agg} = p^{conf} + p^{coop}. \tag{33}$$

We realize that

$$p^{conf} \geq p_C \geq p_A \geq p^{coop}. \tag{34}$$

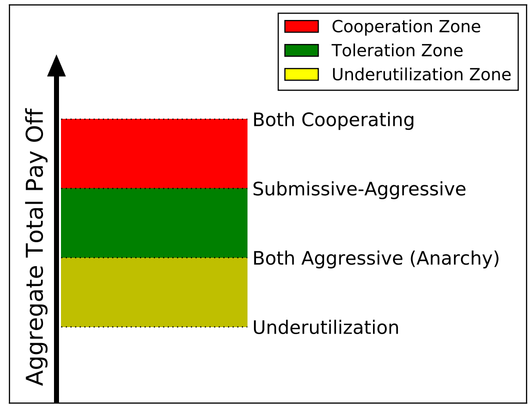


Fig. 4. Aggregate total payoff for TNs with different personalities.

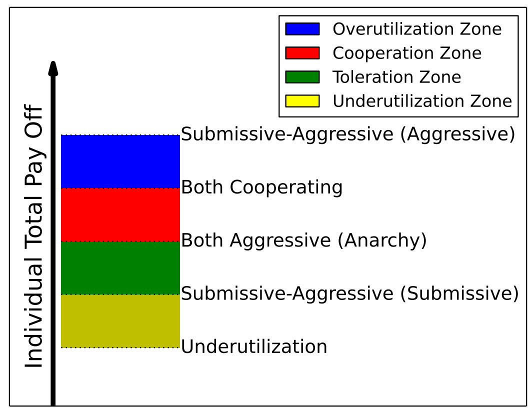


Fig. 5. Individual total payoff for TNs with different personalities.

Here, we see that the cooperating TN may settle to a lower payoff, resulting a higher payoff for the confronting TN. Although it may seem counter-intuitive, if $p_A - p^{coop} \leq p^{conf} - p_A$, the aggregate payoff is higher than the case of anarchy. This is a critical issue in evolutionary game theory. If the common good, rather than the individual payoffs is to be optimized, yielding to an aggressive TN is better than perpetual confrontation. Hence, if the TNs are to be working together, TNs should not resort to continuous aggression.

Note that the aggregate total payoff of the system cannot exceed $2mp_C$ and individual total payoffs of the TNs are limited by mp_C. Aggregate total payoffs and individual total payoffs of different are presented in Fig. 4 and 5 respectively.

As we can see in Fig. 4, tolerating an aggressive TN is not the worst case scenario. Making payback mechanisms permanent, i.e., anarchy, may reduce the aggregate total payoff of the MCN. Depending on the degree of cooperation, TNs may approach the cooperating limit. We also notice that in this game, cooperation is both the *Pareto-Optimal* and the *Nash Equilibrium* strategy, i.e., they both receive the maximum payoff and both TNs cannot increase their performance without degrading the performance of the other. Hence, as long as it is possible, cooperation is the only rational strategy of the TNs. However, if cooperation is not possible, toleration is still better than anarchy. Anything below anarchy is underutilization of the resources.

Note that evolutionary game theory suggests a strategy is good only if it is effective against other alternating strategies [17]. Perpetual uncooperation is an alternating strategy against which retaliation does not effectively work, especially if the TNs collaborate

In Fig. 5, we notice that there is one more region: Overutilization. The *overutilization zone* is the extra payoff of an aggressive TN, when pitted against a submissive TN. Overutilization of one TN is compensated by toleration of the other. If TNs act properly, their individual gains should not fall below the *Anarchy* line. Note that any point below the anarchy line is underutilization of the resources.

VI. Numerical Results

A. Uniterated two transmitters game

In Section III, we reached cooperative payoff, p_C, and anarchic payoff, p_A. We also showed that they only depend on the $\frac{A_1}{C_{eq}}$ and $\frac{A_2}{A_1}$ ratios. In this section, we provide numerical results for the uniterated two transmitters game.

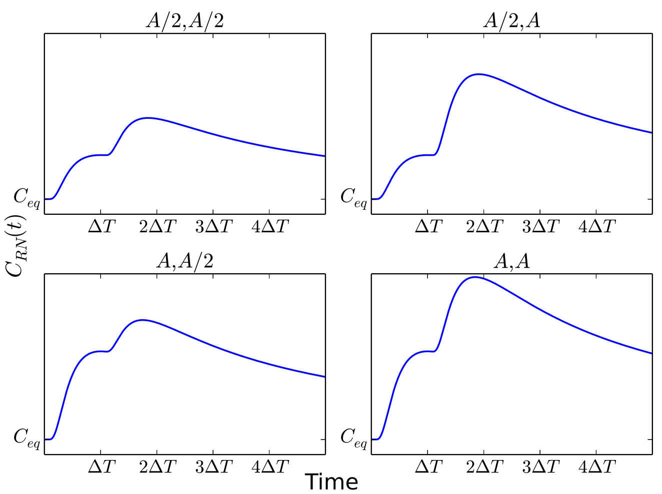


Fig. 6. Carrier concentration at the receiving node due to different actions taken by TNs.

Fig. 6 gives us the concentration around the receiver for $D = 1$, $\Delta T = 1$, $\frac{A_1}{C_{eq}} = 100$, $\frac{A_2}{A_1} = 2$ and saturation ratio $\alpha = 4$. Using these parameters, we can calculate the payoff matrix for this game. The payoff matrix is presented in Table II.

Using (10) and (11), we realize that $p_C = 0.785$ corresponding to $\frac{A}{2}$, A and $p_A = 0.715$ corresponding to A, A. Any coordination set up in this system may improve the system performance at most 9.7%.

If the system has a different saturation ratio, there is a chance that coordination strategy switches from $\frac{A}{2}, A$ to A, A, i.e., coordination strategy converges into Nash equilibrium. The two strategies and their difference is given in Fig. 7. Hence, for the uniterated two transmitters game, coordination

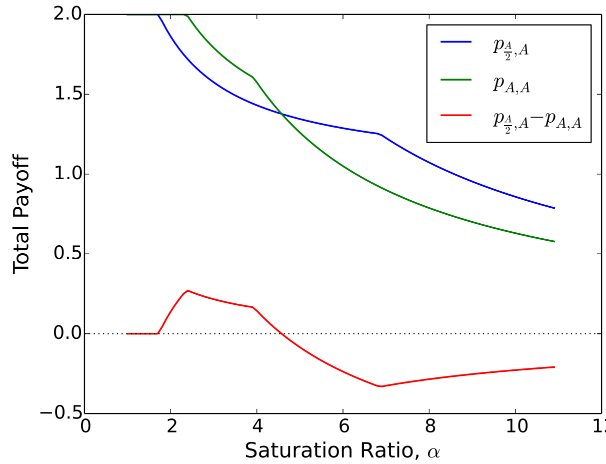


Fig. 7. Saturation ratio vs. total payoff for both nodes for different strategies.

offers marginal increase in the system throughput. *Anarchy* may be easier and simpler solution for MCN.

TABLE II
PAYOFF MATRIX FOR THE NUMERICAL EVALUATION PARAMETERS

		TN$_2$ A/2		TN$_2$ A	
TN$_1$	A/2	0.98	0.41	0.98	0.59
TN$_1$	A	1	0.33	1	0.43

B. Iterated two transmitters game

In Section IV, we elaborated on iterated two transmitters game, in which TNs had tools to ensure cooperation. We focused on three different strategies to ensure cooperation and counter misunderstandings between cooperative TNs. For the parameters given in the previous subsection, payback, reconciliation and forgiving cooperation techniques are analyzed below.

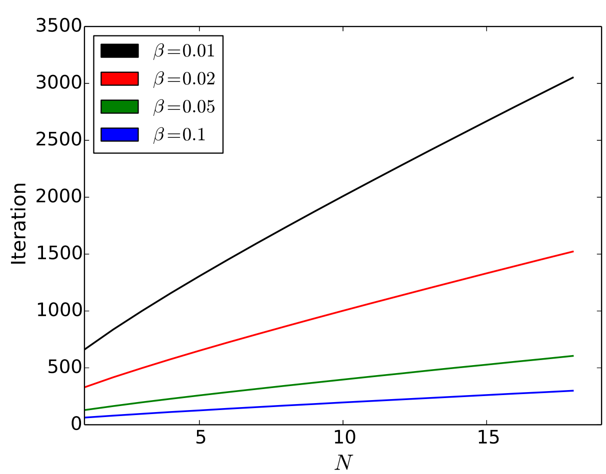


Fig. 8. Inevitable Confrontation Iteration vs N of *tit for N tat* for different misunderstanding probabilities, β values. Here, y-axis shows the iteration where the cumulative confrontation probability exceeds 99%.

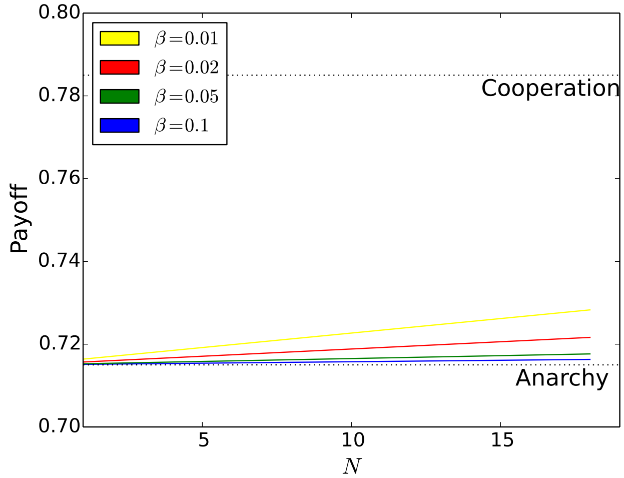


Fig. 9. Per iteration payoff vs N of *tit for N tat* for different misunderstanding probabilities, β values.

As we can see in Fig. 8, as the iteration number increases, regardless of misunderstanding rate or N, confrontation becomes inevitable. In channels with high misunderstanding rate, β, confrontation may even occur within the first 100 iteration, while low misunderstanding rate and high N, confrontation may be delayed. In Fig. 9, we realize that even in channels with low β, per iteration payoff is only marginally above the anarchy line.

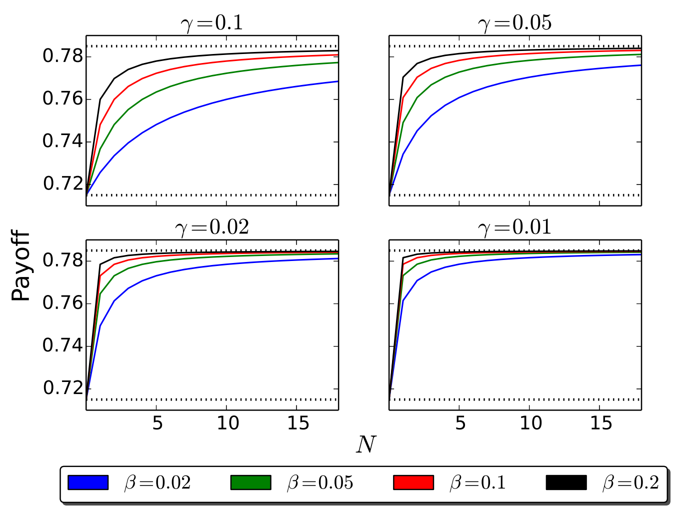


Fig. 10. Per iteration payoff vs N of *tit for N tat* for different misunderstanding probabilities, β values and forgiving probabilities, γ values.

Fig. 10 shows us how reconciliation affects the per iteration payoff. Even in channels with high β, reconciliation may dramatically increase the per iteration payoff, even approaching to cooperation limit for high N values.

In Fig. 11, we present the payoff per iteration for forgiving TNs. The anarchy line is too low to be seen on the figures. Although M increases the payoff, even for the lowest values of M and S, payoff is only marginally below the cooperation limit. Even for $M = 2$, $S = 2$ and $\beta = 0.1$, the payoff is only 0.13% lower than the cooperation limit.

In Fig. 12 and 13, we numerically evaluate the zones we

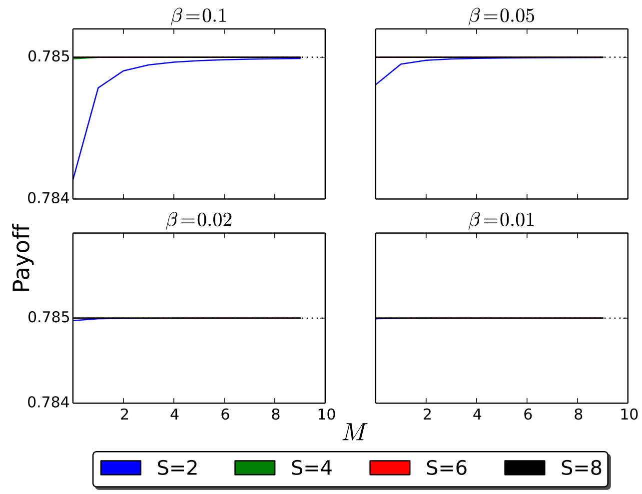


Fig. 11. Per iteration payoff vs M of consecutive cooperation target for different number of aggressions to the confrontation, S values and misunderstanding probabilities, β values.

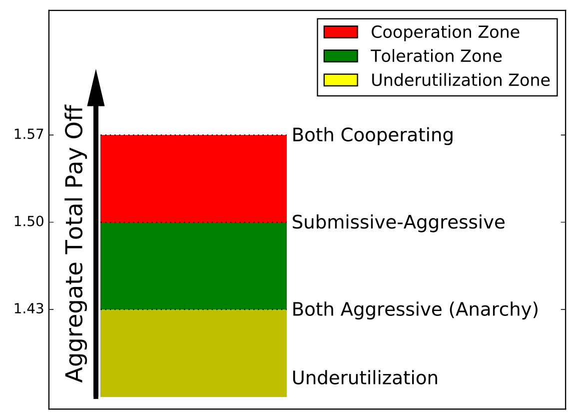


Fig. 12. Aggregate total payoff for TNs with different personalities for numerical evaluation parameters

derived in section V. Note that the zones are not necessarily distributed evenly. Here, we verify that perpetual aggression hurts the overall performance of the system.

VII. Conclusion

In this paper, we analyzed anarchy vs. cooperation in Internet of Molecular Things with a game-theoretic approach. We showed that although cooperation naturally wields the best results, ensuring cooperation is not easy even if both parties try to cooperate in case there is a probability of accidental aggression. In these situations, lacking of a payback mechanism may result in one of the nodes taking advantage of the other. However, if the payback mechanism is not well adjusted, it may turn accidental aggressions to all out confrontation. We found out that tit for tat strategy is costly and offer only a marginal gain over anarchy. Forgiving and reconciliating strategies offer superior performance in preventing a system from perpetual confrontation and reconciliating nodes require minimum hardware to implement.

Although the numerical results are evaluated only for an isotropic, 2D medium with no flow, if medium specific simu-

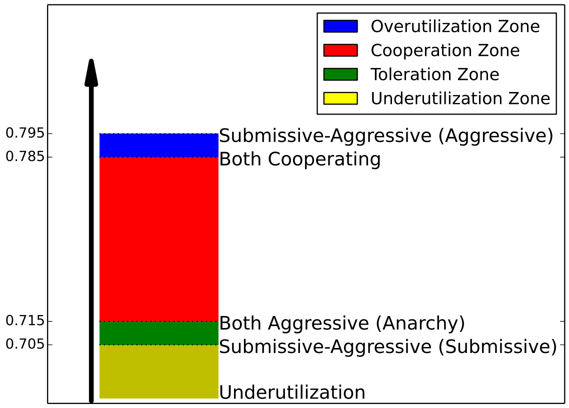


Fig. 13. Individual total payoff for TNs with different personalities for numerical evaluation parameters

lations are performed, the design and transmission principles stated in this work would hold.

In this work, we realized that although anarchy is achieved naturally, cooperation requires prior protocols and application specific hardware. Due to the size and energy constraints of nanomachines, implementing such systems may be costly. However, depending on the environment and design parameters, establishing such systems may offer significant performance increase. Hence, in some cases, specific hardware to achieve cooperation may be included in the nanomachine design.

Finally, we deduced that perpetual confrontation hurts the aggregate payoff. In case it is pitted against an uncooperative transmitter, oppressed transmitter should act submissive to improve system performance.

References

[1] I. F. Akyildiz, F. Brunetti, and C. Blazquez, "Nanonetworks: A new communication paradigm," *Comp. Netw.*, vol. 52, no. 12, pp. 22602279, 2008.

[2] M. Pierobon and I. F. Akyildiz, "Diffusion-based noise analysis for molecular communication in nanonetworks," *IEEE Trans. Signal Process.*, vol. 59, pp. 25322547, 2011.

[3] B. Atakan, S. Balasubramaniam, and O. B. Akan, "Body area nanonetworks with molecular communications in nanomedicine," *IEEE Commun. Mag.*, vol. 50, no. 1, pp. 2834, Jan. 2012.

[4] M. Kuscu, O. B. Akan, "The Internet of Molecular Things Based on FRET," *IEEE Internet of Things Journal*, vol. 3, no. 1, pp. 4-17, February 2016.

[5] A. W. Eckford, "Nanoscale communication with brownian motion," in *Proc. 41st Annu. Conf. Inf. Sciences Syst.*, 2007, pp. 160165.

[6] B. Atakan and O. B. Akan, "On channel capacity and error compensation in molecular communication," *Trans. Comput. Syst. Biol. X*, vol. 5410, pp. 5980, 2008.

[7] A. W. Eckford, N. Farsad, S. Hiyama, and Y. Moritani, "Microchannel molecular communication with nanoscale carriers: Brownian motion versus active transport," in *Proc. IEEE Int. Conf. Nanotechnol.*, 2010.

[8] L. P. Gin and I. F. Akyildiz, "Molecular communication options for long range nanonetworks," *Computer Netw.*, vol. 53, pp. 27532766, 2009.

[9] D. Kilinc and O. B. Akan, "An information theoretical analysis of nanoscale molecular gap junction communication channel between cardiomyocytes," *IEEE Trans. Nanotechnol.*, vol. 12, no. 2, pp. 129136, Mar. 2013.

[10] M. Gregori and I. F. Akyildiz, "A new nanonetwork architecture using flagellated bacteria and catalytic nanomotors," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 4, pp. 612619, 2010.

[11] R. A. Bressan, H. C. Park, F. Orsini et al. "Biotechnology for mechanisms that counteract salt stress in extremophile species: a genome-based view", *Plant Biotechnology Reports*, vol. 7, no. 1, pp. 27-37, 2013.

[12] S. E. Jorge-Villar and H. G. M. Edwards, "Lichen colonization of an active volcanic environment: a Raman spectroscopic study of extremophile biomolecular protective strategies." *J. Raman Spectrosc.*, vol. 41, pp. 63-67, 2010.

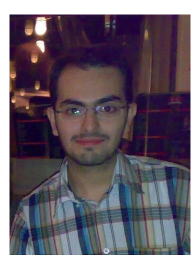
[13] J. W. Weibull, *Evolutinary Game Theory*, Cambridge, MA: MIT Press, 1995.

[14] R. Dawkins and J. R. Krebs, "Arms Races between and within Species", *Proc. R. Soc. B* vol. 205, pp. 489-511, 1979.

[15] A. Wu, D. Liao and R. Austin, "Evolutionary game theory in cancer: first steps in prediction of metastatic cancer progression?", *Future Oncology*, vol. 11, no. 6, pp. 881-883, 2015.

[16] C. Jiang, Y. Chen and K. J. R. Liu, "Nanoscale molecular communication networks: a game-theoretic perspective", *EURASIP Journal on Advances in Signal Processing*, vol. 2015, no. 1, pp. 115, 2015.

[17] R. M. Axelrod, *The evolution of cooperation*, New York, NY: Basic Books, 1984.



Caglar Koca [S'14] received his B.Sc. degree in Electrical and Electronics Engineering from Middle East Technical University, Ankara, Turkey, in 2010 and received his M.Sc. degree in Electrical and Electronics Engineering from Koc University, Istanbul, Turkey in 2014. He is currently a research assistant in the Next-generation and Wireless Communication Laboratory and pursuing his Ph.D. degree at the Electrical and Electronics Engineering Department, Koc University, Istanbul, Turkey. His current research interests include information theory, and Internet of Things.

Ozgur B. Akan [M'00-SM'07-F'16] received PhD degree from the School of Electrical and Computer Engineering, Georgia Institute of Technology, USA, in 2004. He is currently the Head of Internet of Everything (IoE) Group, Electrical Engineering Division, Department of Engineering, University of Cambridge, UK. He is also with the Department of Electrical and Electronics Engineering, Koc University, Istanbul, Turkey. His research interests include wireless, nano, molecular communications, and Internet of Everything.