

Concurrent Transmission Based on Channel Quality in Ad Hoc Networks: A Game Theoretic Approach

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SUMMARY In this paper, a decentralized concurrent transmission strategy in shared channel in Ad Hoc networks is proposed based on game theory. Firstly, a static concurrent transmissions game is used to determine the candidates for transmitting by channel quality threshold and to maximize the overall throughput with consideration of channel quality variation. To achieve NES (Nash Equilibrium Solution), the selfish behaviors of node to attempt to improve the channel gain unilaterally are evaluated. Therefore, this game allows each node to be distributed and to decide whether to transmit concurrently with others or not depending on NES. Secondly, as there are always some nodes with lower channel gain than NES, which are defined as hunger nodes in this paper, a hunger suppression scheme is proposed by adjusting the price function with interferences reservation and forward relay, to fairly give hunger nodes transmission opportunities. Finally, inspired by stock trading, a dynamic concurrent transmission threshold determination scheme is implemented to make the static game practical. Numerical results show that the proposed scheme is feasible to increase concurrent transmission opportunities for active nodes, and at the same time, the number of hunger nodes is greatly reduced with the least increase of threshold by interferences reservation. Also, the good performance on network goodput of the proposed model can be seen from the results.

key words: Ad Hoc networks, game theory, Nash Equilibrium Solution, concurrent transmission

1. Introduction

Wireless communication enables us to enjoy the convenience of mobile life wherever you are. The IEEE 802.11 standard defines two connection ways: infrastructure and Ad Hoc. Ad Hoc [1], [2] means a collection of nodes cooperatively communicate with each other without any pre-established infrastructure such as a centralized access point. A key design objective in Ad Hoc networks is to achieve high network throughput while keeping low collisions, packets drop ratio and transmission delay [3], [4]. However, with traditional 802.11 series media access control scheme like DCF (Distributed Coordination Function), a transmitting in wireless networks inevitably affects others

due to the shared spectrum. Even small wireless devices can cause strong interferences to others thus severely decrease overall throughput [5], [6]. Further, competitive channel usage also causes other extra volatility and adverse effects in wireless links leading to critical performance degradation on packets transmission delay, delivery ratio and so on.

The reason behind the poor performance of competitive access protocols on network throughput is its conservative treatment of potential interferers. For instance, when using RTS/CTS handshakes as contention resolve solution, all neighbors should be silent during the period indicated by Network Allocation Vector (NAV). To overcome this problem, researchers mostly considered the use of Transmission Power Control (TPC) [4], [7], [8] on selected nodes as a way to improve the spatial re-usage leading to a great gain of throughput. However, real-time adaptive TPC still remain theoretical on devices implementation and is only feasible in special scenario with great hardware complexity. Most devices should reboot or ask human intervention to adjust their powers by modifying the chip's Management Information Base (MIB) item. On the contrary, to change the power with higher cost, we can readily observe the channel quality variations. In fact, under different communicating environments with various fadings, packets can experience frequent channel quality changes within the exchanging process from sources to destinations. With different networks access manners, radio reflections, refractions and scattering influences existent, the value of channel gain often changes within a large range instead of remaining constant. For example, Zigbee, 802.11x, wireless USB and Bluetooth all choose 2.4 GHz (2.4→2.483 GHz) as their working frequency and interfere each other more or less even with frequency hopping, code division or prospective cognitive radio technologies. According to the aforementioned reasons, channel volatility is unavoidable in wireless communication environments.

2. Motivation

Traditional researches treat channel quality volatility as a bad effect on signal transmission and name such phenomena fading [9], [10]. Instead, in this paper, fading is regarded as a beneficial factor and to be utilized to improve throughput by concurrent transmitting based on game theory. That is, a threshold of channel quality, namely NES in the game, is found to decide the qualified candidates for concurrent transmissions. From a game theory perspective, the main

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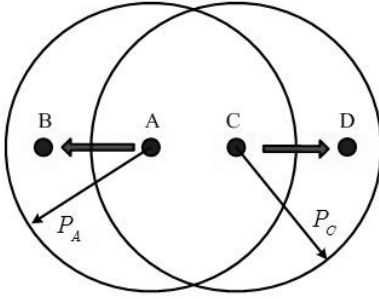


Fig. 1 Example of 4-nodes concurrent transmissions.

advantages of our design are that, by turning nodes into selfish players for pursuing high throughput based on channel gain threshold, an otherwise complex system can reach efficient outcomes in a lightweight and distributed manner.

As shown in Fig. 1, it is the example from multiple concurrent transmissions in a shared channel in Ad Hoc networks. There are four nodes, marked as A, B, C and D. P_A and P_C denote A and C's transmitting power respectively. It is assumed that A and C wish to transmit to B and D respectively. A and C are within the maximum transmission range of each other. Assuming a two-ray ground propagation model and considering Additive White Gaussian Noise (AWGN) with mean 0 and variance σ^2 , the communication pairs of A→B and C→D are not allowed to proceed concurrently regarding capture effect. However, in fact, when CSMA/CA access strategy is disabled, there is still opportunity for the two pairs to transmit simultaneously and successfully if they experience different fading and Signal to Interference and Noise Ratios (SINR) of them are both met.

SINR model proposed in this paper, formulated as Eq. (1), can be used to explain the motivation in detail. For a successful reception, the SINR model needs a minimum signal to interference and noise ratio $SINR_{th}$, which should satisfy the SINR threshold of receivers in each concurrent transmission pair. SINR of node i is defined as γ_i and successful concurrent packets delivery occurs only when Eq. (1) holds:

$$\gamma_i = \frac{h_i P_i}{\alpha \sum_{j \in \chi_i} h_j P_j + \sigma^2} \geq SINR_{th} \quad (1)$$

where P_i is the power of transmitter i and h_i is the channel gain or channel quality indicator of i . α is the crosstalk interference ratio, χ_i is the set of all interfering nodes for i and σ^2 is the variance of AWGN with mean 0. For mathematical convenience, transmitting power is normalized for all nodes in the analysis and the possibility of concurrent transmission opportunities from channel quality variations is checked..

The rest of this paper is organized as follows. In Sect. 3, we outline previous works of game-theory applications on TPC. In Sect. 4, a brief introduction of game theory is given and the proposed channel-quality-based static concurrent transmission game is introduced. In Sect. 5, the reason of hunger nodes generation and corresponding solving scheme are given. A dynamic implementation strategy for

aforementioned static game is proposed in Sect. 6. Numerical results and discussions are showed in Sect. 7 followed by conclusion in Sect. 8 and acknowledgement section.

3. Related Works

There mainly exist two categories of schemes related to our works: game-theory-based and TPC-based concurrent transmission proposals. The former can be further classified into three classes: NE-based backoff time adaptation [11], NE-based power control [12], [13], and NE-based transmission schemes depending on channel conditions [14]. Whereas TPC schemes mainly focus on either energy conservation [15], [16] or increasing throughput [4], [8], [17]. Our work can be regarded as a combination of NE-based and throughput-oriented concurrent transmission strategy.

For NE-based determination scheme used in wireless networks especially in Ad Hoc or Wireless Sensor Networks (WSNs), most work has been done around wireless resources allocation such as radio frequency, available bandwidth and transmitting power etc. Generally speaking, any resource limited allocation or assignment problem is candidate for NE determination. Usually, since concurrent transmission opportunity is decided by SINR, the most relevant resources for this determination problem are NE-based power control. Saraydar et al. [18] proposed a game theory based power control algorithm for data transmissions in cellular networks to increase capacity and extend lifecycle. Although the paper was not putting focus on concurrent transmission, the work has been recognized as the basis of followed concurrent transmission research papers because capacity demands is common as concurrent transmission opportunities increasing. F. Wang and M. Krunz [19] proposed G-MAC with adaptive power control to make nodes plan their transmissions simultaneously in an Ad Hoc manner. Their works frame the concurrent transmission problem as a complete information non-cooperative power control game to find the transmitting power threshold meeting SINR need. Sachin et al. [20] proposed a Bayesian game with incomplete interference information about opponents. The game is static, i.e., simultaneous move between nodes, for selecting a power profile over the entire available bandwidth to maximize Shannon capacity. HyungJune Lee et al. [13] developed a channel access game, which considered concurrent transmissions with different access points, under the influence of inter-cluster interferences. After successfully finding the Bayesian Nash Equilibrium, they further presented a simple dynamic implementation procedure for nodes to efficiently find a Nash Equilibrium without knowing the number of total active nodes. The aforementioned works all optimize network utility over power adaptation, whereas we propose the concurrent transmission scheme with a constant transmitting power. Moreover, we do not need complete interference information, which is hard to be obtained in a decentralized environment, between nodes for gaming. Besides, we confirm our work not only in a static game but also give the practical implementation method to

make it feasible.

Another way to achieve concurrent transmission is throughput-oriented TPC schemes. Such protocols in Ad Hoc networks were proposed in the literature [4], [8], [17]. In PCMA [8], a flexible “variable bounded power” collision suppression model is introduced. Each receiver advertises its calculated interference margin by sending busy tone pulses over a separate control channel. The PCDC protocol [17] uses two channels for data and control packets respectively. They do not use the RTS/CTS exchange to silence the neighboring nodes. Instead, collision avoidance information is inserted in the CTS packets and sent over the control channel. The information is used to dynamically bound the transmitting power of potentially interfering nodes in the vicinity of a receiver to allow for interference-limited simultaneous transmissions. Different from the two mentioned multi-channel concurrent transmission schemes, POWMAC [4] uses a single channel for both data and control packets. The scheme adjusts the transmitting power of data packets to allow for some interference margin at the receiver. Therefore, multiple interference-limited transmissions near a receiver are allowed to overlap in time, provided their Multi-Access Interference (MAI) effects do not lead to collisions at nearby receivers.

To our best knowledge, proposed game-theory-based or TPC-based protocols all have not considered how to fully utilize the nature of channel quality variation especially when nodes experience different fading within a symbol or a series of symbols. Our work, although driven by similar game theoretical analysis, is different from most of these protocols in several aspects. First, the transmitting power is fixed throughout communication procedure and normalized for simplicity. Second, incomplete information for channel quality is introduced in our game with no need of knowing all nodes’ exact channel conditions. Third, an implementation method is presented to make our model practical. Another important difference is that all aforementioned works did not consider the nodal hunger phenomenon caused by having no opportunity to take part in concurrent transmission for a long time. Such phenomenon is unfair to hunger nodes especially in a distributed Ad Hoc networks where no one has the privilege to access channel preferentially.

4. Concurrent Transmission Game Based on Channel Quality Variation

To explain our proposed game, we first give a brief introduction to game theory with emphasis on its classification. The concurrent transmission scheme is described followed as a static game.

4.1 Game Theory Basic

Game theory is a collection of mathematical tools to solve the interactive decision problems between rational players. The dominant strategy, an outcome of a game where no player has any extra benefit for just changing its strategy

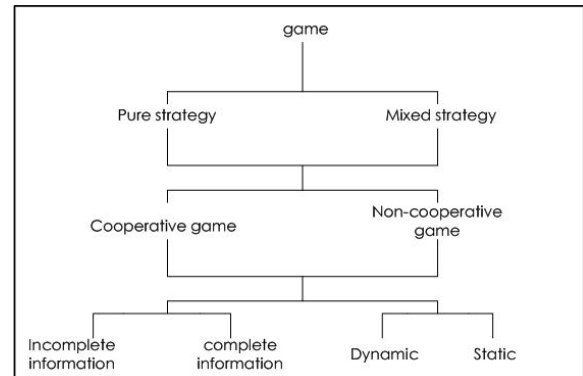


Fig. 2 Game classification.

unilaterally for any determination problems, is Nash Equilibrium [21]. In the last few years, game theory has gained a notable amount of popularity in solving communication and networking issues involving power control, congestion control, routing and other aspects in wired and wireless communications systems.

For different purposes, games can be classified into a tree structure as shown in Fig. 2. At first, by choosing probability, games can be classified to pure Nash Equilibrium, where each user chooses exactly one action (with probability one), and mixed Nash equilibrium, where the choices of each user are modeled by a probability distribution over action profiles. Then, both pure and mixed strategy game can be further divided into cooperative and non-cooperative games. In non-cooperative games, the player can not make commitments to coordinate their strategies. Whereas, a cooperative game is a game where groups of player may be enforced to work together by some incentive mechanism to maximize their utility.

Furthermore, according to the players’ moves, simultaneously or one by one, games can be further classified into two categories: static and dynamic games. For static game, players move by their strategies simultaneously without any information about their opponents. In the dynamic game, players move in a predetermined order and know the moves played by others before they act. Therefore, according to the knowledge of players regarding to all aspects of game, the non-cooperative/co-operative game can be further categorized into complete/incomplete information games. In the complete information game, each player has all the knowledge about their opponents’ characteristics such as strategy profiles, utility functions, price functions etc., but all these information are not necessarily available in an incomplete information game.

4.2 Proposed Concurrent Transmission Scheme

Our work is a non-cooperative static game with incomplete information of channel quality. That is, all nodes will independently decide whether or not to transmit simultaneously based on a NES determined largely by the distribution of channel quality.

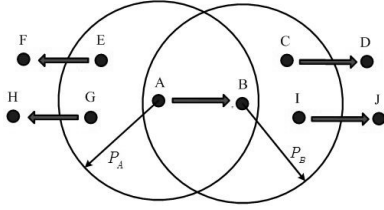


Fig. 3 Example of 10-nodes concurrent transmissions.

4.2.1 Assumptions

Before giving our concurrent transmission model, we first assume that:

- Assumption 1: The channel gain is stationary in the duration of a concurrent transmission.
- Assumption 2: The total amount of active nodes can be obtained by some estimation methods [22], [23].
- Assumption 3: The active concurrent transmission pairs in the same direction, such as C→D and I→J in Fig. 3, could be as far as possible within mutual communication range. Or, the current concurrent transmission pairs should be scheduled for the opposite direction like A→B and C→D in Fig. 1.

The first assumption considers the most common channel fading, say block fading (independent fading can be regarded as a block fading with length of 1 symbol), and the block length can be adjusted in our model for different scenarios. The second assumption implies that number of active nodes n should be known to make our game feasible. The third assumption gives the premise for concurrent transmission in Ad Hoc manner. Under this assumption, nodes can obtain more simultaneous transmission opportunities by meeting mutual interference margin at best effort.

4.2.2 Static Game

In this subsection, we introduce a non-cooperative, incomplete information static game and take nodes as selfish players who try to maximize their own utilities. We assume that each node is rational and self-interested, and chooses a transmission strategy independently and simultaneously.

Definition 1: We formulate a Bayesian Interference Channel Access Game as follows:

1. Players: active node $i, i \in \{1, 2, \dots, n\}$, have channel gain $h_i > 0$.
2. Actions: $a_i = \{T, W\}$ for all players. T represents transmitting and W represents backoff.
3. Utility function:

$$u_i(a_i, \mathbf{a}_{-i}; h_i) = \begin{cases} \prod_{i=1}^n (W, \mathbf{a}_{-i}) = 0 & , & a_i = W \\ \prod_{i=1}^n (T, \mathbf{a}_{-i}) = R_i(a_{-i}) - c(P_i), & a_i = T \end{cases} \quad (2)$$

We use Shannon's capacity (maximum achievable rate) as networks throughput expressed by

$$R_i(\mathbf{a}_{-i}) = \begin{cases} \log(1 + \gamma_i) & \gamma_i \geq SINR_{th} \\ 0 & otherwise \end{cases} \quad (3)$$

where $\chi_i = \{j \neq i : a_j = T\}$. $c(P_i)$ is the price function expressed as $c(P_i) = \mu P_i / h_i = \mu / h_i$. μ is defined as the coefficient of the price. We assume transmitting power is fixed, say $P_i = 1$.

Definition 2: $\{a_i^*(h_i)\}_{i=1}^n$ is a Bayesian Nash Equilibrium if and only if:

$$\begin{aligned} a_i^*(h_i) &\in \arg \max_{a_i} \sum_{\mathbf{h}_{-i}} p_i(\mathbf{h}_{-i} | h_i) \cdot u_i(a_i, \mathbf{a}_{-i}^*(\mathbf{h}_{-i}); h_i, \mathbf{h}_{-i}) \\ &= \arg \max_{a_i} E \left[\prod_{i=1}^n (a_i, \mathbf{a}_{-i}^*(\mathbf{h}_{-i}) | h_i) \right] \end{aligned} \quad (4)$$

for all h_i and players i . where $p_i = p_i(\mathbf{h}_{-i} | h_i)$ is the conditional probability of other players' channel quality \mathbf{h}_{-i} under h_i , named as player i 's belief. In this game, each node knows the probability distribution of others channel gain vector $\mathbf{h}_{-i} = (h_1, \dots, h_{i-1}, h_{i+1}, \dots, h_n)$ and its own channel gain h_i from the feedback of previous transmission. Finally, the utility function of player i is as follows.

$$v_i = \sum_{\mathbf{h}_{-i}} p_i(\mathbf{h}_{-i} | h_i) \cdot u_i(a_i, \mathbf{a}_{-i}; h_i, \mathbf{h}_{-i}) \quad (5)$$

Proposition: In a Bayesian Nash Equilibrium, player i will choose transmitting if and only if there exists a channel gain threshold h_{th} so that:

$$\begin{aligned} E \left[\prod_{i=1}^n (T, \mathbf{a}_{-i}^*(\mathbf{h}_{-i}) | h_i) \right] &\geq E \left[\prod_{i=1}^n (W, \mathbf{a}_{-i}^*(\mathbf{h}_{-i}) | h_i) \right] \\ a_i^*(h_i) &= \begin{cases} T, & h_i \geq h_{th} \\ W, & h_i < h_{th} \end{cases} \end{aligned} \quad (6)$$

Proof: The expected utility is as follows when player i choose to transmit:

$$\begin{aligned} &E \left[\prod_{i=1}^n (T, \mathbf{a}_{-i}(\mathbf{h}_{-i}) | h_i) \right] \\ &= \sum_{\chi_i \cup \overline{\chi_i} = \{1, \dots, n\} - \{i\}} \prod_{j \in \chi_i} p(a_j(h_j) = T) \prod_{j \in \overline{\chi_i}} p(a_j(h_j) = W) \cdot \\ &p \left(\frac{h_i}{\alpha \sum_{j \in \chi_i} h_j + \sigma^2} \geq SINR_{th} \mid \{a_j(h_j) = T, \forall j \in \chi_i\} \right) \\ &\cdot E \left[\log \left(1 + \frac{h_i}{\alpha \sum_{j \in \chi_i} h_j + \sigma^2} \right) - \frac{\mu}{h_i} \mid \{a_j(h_j) = T, \forall j \in \chi_i\}, \sum_{j \in \chi_i} h_j \leq \frac{1}{\alpha} \left(\frac{h_i}{SINR_{th}} - \sigma^2 \right) \right] \end{aligned} \quad (7)$$

Where $\chi_i = \{j \neq i : a_j = T\}$ and $\overline{\chi_i} = \{j \neq i : a_j = W\}$. The expected utility for transmitting is increasing by h_i whereas the expected utility for W is 0. Therefore, when

$E[\prod_{i=1}^n (T, \mathbf{a}_{-i}(\mathbf{h}_{-i}) | h_i)] \geq 0 \Leftrightarrow h_i \geq h_{th}$, we can always find the solution to the expression $E[\prod_{i=1}^n (T, \mathbf{a}_{-i}(\mathbf{h}_{-i}) | h_{th})] = 0$, say the transmission threshold h_{th} as NES.

4.2.3 Analysis for Concurrent Transmission Instances

Here, we will design a concurrent transmission game and derive the Bayesian Nash Equilibrium based on above analyses. The first scenario includes only two nodes for simplicity and then the number of nodes will be increased to $n > 2$ in the second scenario.

(1) $n = 2$: We assume that there are two active nodes i and j within transmission range of each other and the concurrent transmission threshold is h_{th} . There are two possible conditions as follows:

$$\begin{aligned} h_j < h_{th}, u_{ts1} &= \log(1 + h_i/\sigma^2) - \mu/h_i \\ h_j \geq h_{th} \begin{cases} h_j \leq h'_{th}, u_{ts2} &= \log(1 + h_i/(h_j + \sigma^2)) - \mu/h_i \\ h_j > h'_{th}, u_{tf} &= 0 - \mu/h_i \end{cases} \end{aligned} \quad (8)$$

where $h'_{th} = h_i/SINR_{th} - \sigma^2$. In first case, when $h_j < h_{th}$, node j should choose W . Therefore, due to $\gamma_1 = \frac{h_i}{\sigma^2} \geq SINR_{th}$, the resulting utility of i is $u_{ts1} = \log(1 + h_i/\sigma^2) - \mu/h_i$. When $h_j > h_{th}$, there are two subcases should be investigated. In subcase 1, the utility of i is $u_{ts2} = \log(1 + h_i/(h_j + \sigma^2)) - \mu/h_i$ when $h_j < h'_{th}$. That means both transmissions of i and j are successful because $\gamma_2 = \frac{h_i}{h_j + \sigma^2} \geq SINR_{th}$ and $h_j \leq h'_{th} = \frac{h_i}{SINR_{th}} - \sigma^2$; In subcase 2, node i fail to transmit concurrently with j due to $\gamma_2 = \frac{h_i}{h_j + \sigma^2} < SINR_{th}$. Thus, there is only price but award in utility $u_{tf} = 0 - \frac{\mu}{h_i}$ when $h_j > h'_{th}$.

As a result, the expected utility of node i in scenario 1 will finally be:

$$\begin{aligned} E(\prod(T, a_j(h_j)) | h_i) &= p(h_j < h_{th}) [\log(1 + \gamma_1) - \mu/h_i] \\ &+ p(h_j \geq h_{th}) [p(\gamma_2 \geq SINR_{th} | h_j \geq h_{th}) \\ &\cdot E(\log(1 + \gamma_1) - \mu/h_i | h_{th} \leq h_j \leq h'_{th}) \\ &+ P(\gamma_2 < SINR_{th} | h_j \geq h_{th}) (0 - \mu/h_i)] \\ &= F_e(h_{th}) [\log(1 + \gamma_1) - \mu/h_i] \\ &+ \bar{F}_e(h_{th}) [F_e(h'_{th} - h_{th}) \\ &\cdot E(\log(1 + \gamma_2) - \mu/h_i | h_{th} \leq h_j \leq h'_{th}) - \mu/h_i] \end{aligned} \quad (9)$$

where we define $F_e(x)$ the cumulative probability distribution for an exponential random variable x , and $\bar{F}_e(x) = 1 - F_e(x)$. In Eq. (9), if node i chooses wait

$$E(\prod(W, a_j(h_j)) | h_i) = 0 \quad (10)$$

Node i will choose to transmit if and only if

$$E(\prod(T, a_j(h_j)) | h_i) \geq E(\prod(W, a_j(h_j)) | h_i) \quad (11)$$

(2) $n > 2$: In this scenario, we consider n active nodes, which are within transmission range of each other, competing for concurrent transmitting opportunities. Here, we define a random variable $H_k = \sum_{i=1}^k h_i \sim \text{Gamma}(k, \frac{1}{\lambda})$ consisting of k independent identically distributed channel gains. The probability density function of H_k is $p(H_k = x) = \frac{\lambda e^{-\lambda x} (\lambda x)^{k-1}}{(k-1)!}$. The cumulative distribution function and the conditional cumulative distribution function of H_k are denoted by $F_{g,k}(x)$ and $F_{g,k}(x | \Gamma)$ respectively. The expected utility of node i in scenario 2 is:

$$\begin{aligned} E(\prod_i(T, \mathbf{a}_{-i}(\mathbf{h}_{-i})) | h_i) &= \sum_{k=0}^{n-1} \binom{n-1}{k} \bar{F}_e(h_{th})^k F_e(h_{th})^{n-1-k} \\ &\cdot [F_{g,k}(H'_{th} | \Gamma_k) \cdot E(\log(1 + \gamma_i) | \Gamma_k, H_k \leq H'_{th}) - \frac{\mu}{h_i}] \end{aligned} \quad (12)$$

where

$$\begin{aligned} \Gamma_k &= \left\{ \begin{array}{l} h_{j_1} \geq h_{th}, h_{j_2} \geq h_{th}, \dots, h_{j_k} \geq h_{th}, \\ \text{and } h_{j_{k+1}} < h_{th}, h_{j_{k+2}} < h_{th}, \dots, h_{j_{n-1}} < h_{th} \end{array} \right\} \\ \gamma_i &= h_i / (\alpha H_k + \sigma^2) \\ H'_{th} &= (h_i / SINR_{th} - \sigma^2) / \alpha \end{aligned} \quad (13)$$

5. How to Treat Hunger Nodes

Although we can obtain the concurrent transmission threshold based on aforementioned static game, there always will be some nodes, just like transmission failure of node i analyzed in Eq. (8) when $h_j \geq h_{th}$ and $h_j > h'_{th}$, failing to attempt to access to the channel. The failure comes from overestimated threshold or underestimated interferences due to the nature of Bayesian Nash Equilibrium for just knowing the probability distributions of others' strategies. We define the nodes as hunger nodes when they continuously experience failures in concurrent transmitting attempts. The exact definition for hunger nodes will be given later.

The larger the number of hunger nodes in networks, the more the fairness for nodes access to the channel will be broken. Furthermore, the overall performance of throughput and transmission delay will be ruined. Therefore, the better performance can be expected with a hunger suppression scheme as follows.

5.1 Interferences Reservation

In Eq. (2), we denote the cost of transmitting power by $c(P_i)$, which is also named as price function to make the game convergence. In order to disclose the relation between price and Nash Equilibrium, we further design the price function as $c(P_i) = \mu P_i / h_i = \mu / h_i$. The definition has a two-fold meaning, one for cost for each transmitting attempt indicated by μ and another for denoting the relation

that channel quality is in inverse proportion to the transmitting cost or price. That is, the better the channel quality is, the less cost is needed for nodes to transmit. For instance, given an error-free or a lower bit error rate channel, we will make less effort to transmit the packets with no need of complex source/channel coding, interleaving, amplifying etc. Moreover, to solve the hunger nodes problem, we further introduce a “hunger factor” C_h into price to reflect the nodal hungry level in networks. The revised price formula can be expressed as follows.

$$C(P_i) = \frac{\mu \cdot C_h}{h_i} \quad (14)$$

Where C_h denotes the number of hunger nodes in networks and is initialized to 0. Then, we define the hunger nodes as: **Definition 3:** Hunger nodes are the nodes who have failed to attempt to transmit for C_{th} times.

The C_{th} threshold can be obtained by a counter embedded in nodes. We can set the value of this threshold based on the network scale or load. The Eq. (14) implies that all other “non-hungry” nodes will pay some extra prices for the hunger nodes if their already scheduled concurrent transmissions will not be influenced. We call this strategy an interference reservation for hunger nodes. The Eq. (14) means those nodes, which can successfully take part in the concurrent transmission based on our presented game, pay extra prices for “caring for” the hungers. The Eq. (14) will reduce to the definition of $c(P_i)$ in Eq. (2) when hunger nodes disappear finally.

Next, we will disclose the influence of interferences reservation to calculated concurrent transmission threshold.

5.2 Cooperative Relay for Hunger Nodes

Although we have proposed interferences reservation scheme for suppressing hunger nodes, there are still cases in which hunger nodes can not access to the channel till they can find some ways to make their channel quality better than calculated threshold. To strengthen our interferences reservation strategy, the hunger nodes have an optional choice. The best candidate is cooperative relay of which we can take advantage to reach the required channel gain without power control or other skills sever destroying game’s nature, say rationality and selfishness. The relay selection method has two steps: at first, if there also are hunger nodes within communication range of the one requiring relay, the top choice is them. Secondly, for the case in which no any hunger node is around, the relay is selected from “non-hungry” active nodes in the vicinity with the best channel quality. To simply provide incentive to relay nodes, the price function is further extended to Eq. (15) as follows.

$$C(P_i) = \frac{\mu \cdot C_h}{h_i \cdot (k \bmod n)} \quad (15)$$

where K is a counter to count the times for the node acting as a relay and n is the number of active nodes. Eq. (15) implies that the more times you have acted as relay, the less price you will pay for transmitting. Therefore, the price Eq. (15)

has only effect on those relays.

The relay scheme can select Decode-and-Forward (DF) as candidate and schedule the transmission in Time Division Duplex (TDD) model. That is, issuing S->(R,D) in first slot and R->D in second slot, where -> express transmitting behavior and S, R, D denote source, relay and destination respectively. To meet the requirement for concurrent transmission, the SINR in receivers should satisfy the following inequality.

$$\Gamma_S^{D(DF)} > SINR_{th} \quad (16)$$

where $\Gamma_S^{D(DF)}$ is

$$\Gamma_S^{D(DF)} = \Gamma_S^{D(Direct)} + \Gamma_{S,R}^D \quad (17)$$

$SINR_{th}$ denotes the SINR threshold at receiver. $\Gamma_S^{D(DF)}$ expresses the SINR at receiver which is a combination of SINR from S->D, say $\Gamma_S^{D(Direct)}$, and R->D, say $\Gamma_{S,R}^D$.

6. A Dynamic Implementation Strategy of Static Game

Static game can only find the equilibrium points when nodes simultaneous move and it is not efficient and reasonable to use only static game in practical packets switching networks in which packets exchanging continuously generate. So, a way to implement our proposed game should be given to make it practical. In this section, based on the idea from trading on the stock market, we propose a simple implementation method. We define the determination procedure for finding a transmission threshold of all participating nodes as an “auction period”. The word indicates the duration in which an agreement of opening share prices between buyers and sellers will be made. Here, we obtain the final threshold through control packets exchanging between trading participants, say nodes, and decide the final threshold just before the end of the “auction period”. The procedure can be explained in detail by Fig. 4. The auction period consists of 3 types of control packets: RTS (Request To Send), CTS (Clear To Send) and CCTS (Concurrent Confirm To Send). The RTS/CTS frames are modified

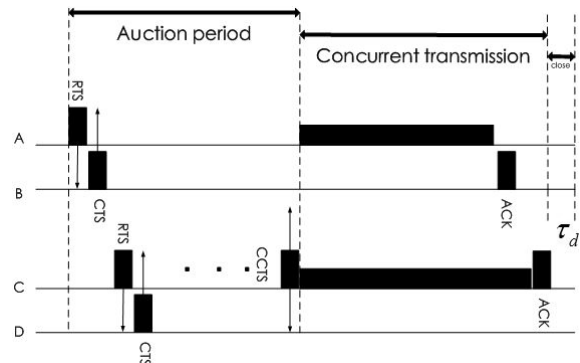


Fig. 4 Auction procedure for dynamic determination.

by adding fields for channel gains and residual time of auction period in their packets headers. The RTS/CTS packets exchange between each sending/receiving pair active in the auction period. Therefore, the participants are decided by their communication ranges. In such case, the channel gain of each active link between participants can be collected by the node received the last RTS. We name it Determination Node (DN). At last DN can give the final decision of concurrent transmission threshold with aforementioned static game and then broadcasts the result by broadcasting CCTS packet in network. According to the received threshold, any participant can decide whether sending in following concurrent transmission stage or not. After the concurrent transmission stage, the next auction turn will be launched followed by a random delay τ_d , where $\tau_d = \text{random}() \times SIFS, \text{random}()$ is a function for generating a number between 0 and 1 and $SIFS$ is the Short Inter Frame Space.

7. Numerical Results and Evaluation

Our performance evaluation can be classified into two categories: one is the simulation to verify the correctness and effectiveness of the model; another is the network scenarios emulation for showing the performance improvement on network goodput.

7.1 Algorithm Performance Analysis

The simulation parameters for algorithm evaluation are listed in Table 1, where α rates the cross-interferences between source node and other transmitting nodes; $SINR_{th}$ indicates the SINR threshold for receivers decoding the packets correctly; Iteration steps denote the number of runs of Monte Carlo tests to approach statistical average; μ in price formula is fixed to 1 for simplicity; σ is the standard deviation of AWGN and the optimization resolve function, by which convergence rate will be greatly influenced, is F_{solve} [24]; Hunger nodes determination threshold C_{th} is fixed to 2 for our low density network; Number of active nodes are 16 and they are shown in Fig. 5; Transmission range is 300 meters which is a typical value for Ad Hoc networks.

Figure 6 shows the influence of different values of α to calculated concurrent transmission thresholds. Note that the bigger the α , the bigger the resulted threshold under the same number of active nodes. The reason is that the increasing of α will attenuate the SINR so that the corresponding thresholds decrease. However, when α is bigger than 0.1, the curves begin to fluctuate dramatically and the direct proportion relation between α and threshold does not

exist. From the assumption 3 defined in Sect. 3, we can say a cross-interference ratio bigger than 0.1 has destroy the premise that the concurrent transmitting nodes are either as far as possible or issuing packets in the opposite directions.

Figure 7 shows the influence of different price formulas to concurrent transmission thresholds. The initial value for C_h is 3 in this simulation. The expression is $C(P_i) = \mu$ for form 1, $C(P_i) = \mu/h_i$ for form 2, $C(P_i) = \frac{\mu \cdot C_h}{h_i}$ for form 3 and $C(P_i) = \frac{\mu \cdot C_h}{h_i \cdot (k \bmod n)}$ for form 4. The curves in Fig. 7 imply that the introduction of channel quality in price can reduce the calculated thresholds. Further, the results from form 3 show higher thresholds than form 2 due to interferences reservation for hunger nodes. Form 4 is a revised version of form 3 by giving incentive awards to relays and shows lower thresholds than that of form 3 but higher than that of form 2.

The impact of $SINR_{th}$ on concurrent transmission thresholds is presented in Fig. 8. A bigger $SINR_{th}$ will result in higher thresholds based on Eq. (2), implying only a small fraction of nodes can transmit concurrently. However, a smaller $SINR_{th}$ lead to a lower thresholds allowing more interferences from other transmitters.

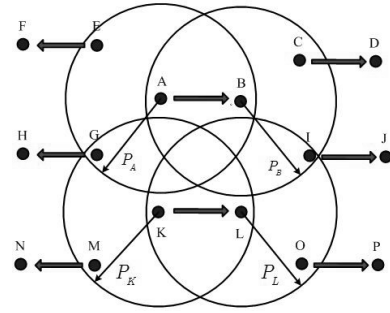


Fig. 5 16-nodes concurrent transmission.

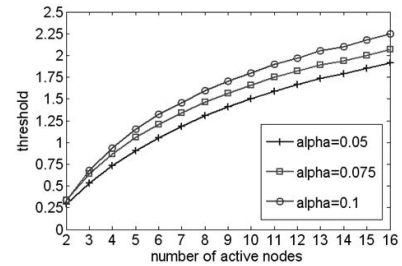


Fig. 6 Influence of α to threshold.

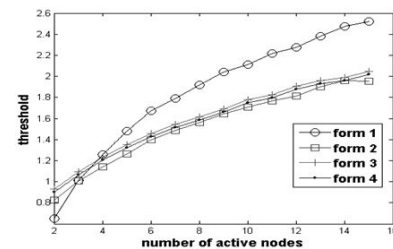


Fig. 7 Influence of different price formula forms to threshold.

Table 1 Algorithm simulation parameters.

name	value	name	value
α	0.1	Iteration times	2000
σ	0.1	μ	1
$SINR_{th}/dB$	10	C_{th}	2
Number of Active nodes	16	Transmission range/m	300

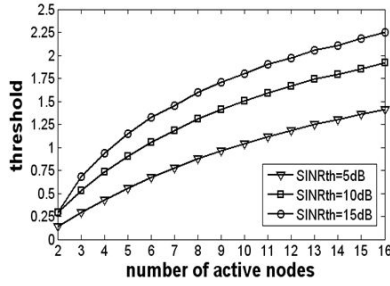


Fig. 8 Threshold versus number of active nodes with different $SINR_{th}$.

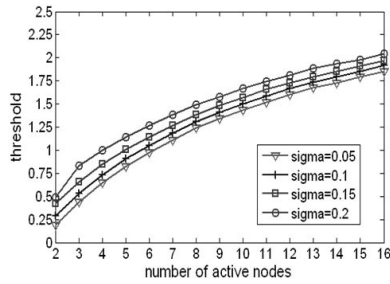


Fig. 9 Threshold versus number of active nodes with different σ .

Table 2 Network performance evaluation parameters.

name	value	name	value
Area/m ²	106	Packets length/ KB	2
Simulation time/s	300	bandwidth/ Mbps	1
Number of active nodes	10	Pass loss	4
SINR threshold/dB	10	Communication radius/m	300
RTS/CTS length/B	30	C_{th}	2
Channel model	Ricean	Coherence time/symbols	2

In Fig. 9, the calculated thresholds increase with the standard deviation of AWGN. Similar to Fig. 8, the smaller the power of noise means the more the nodes could attempt to transmit concurrently with others under a lower calculated threshold.

7.2 Network Performance Evaluation

In this section, we will investigate the network performance of our proposed game model by evaluating the important QoS parameter: network goodput. Network goodput is the application level throughput, i.e. the number of useful bits per unit of time forwarded by the network from a certain source address to a certain destination, excluding protocol overhead, and excluding retransmitted data packets. The topology used in the following simulations is the same as shown in Fig. 3 and parameters are listed in Table 2.

Figure 10 depicts the network goodput versus the packet generation rate for the four examined models, say G-MAC [12], 802.11b [5], POWMAC [4] and our proposed model CTCG (Concurrent Transmission based on Channel Gain). This figure shows that CTCG can obtain a comparable performance with GMAC regarding goodput. When

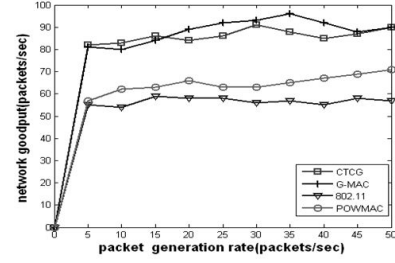


Fig. 10 Network goodput versus packet generation rate for different protocols.

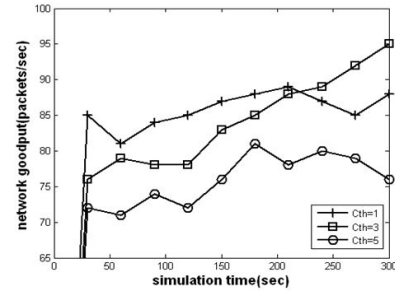


Fig. 11 Network goodput versus simulation time with different C_{th} .

packet generation rate is larger than 15 packets/sec, CTCG shows a little worse performance than GMAC due to the reason as follows. GMAC can actively control the game by dynamically adjusting the transmitting powers but our model is based on the passive knowledge of channel gains with fixed transmitting powers. Therefore, GMAC will outperform our model in most cases but with a great cost of hardware complexity and money investment. Although POWMAC can achieve about 10% improvement in network goodput over the 802.11b standard, it shows approximate 30% performance degradation compared to CTCG and GMAC. The decrease is due to the conservative estimation of the number of candidates for concurrent transmission, which in practice could meet the concurrent transmission requirements, by defining a MTI (Maximum Tolerable Interference) threshold. Among the four models, 802.11b presents the worst goodput obviously due to its contention-based access strategy leading to no any opportunity for concurrent transmissions.

Figure 11 shows the influence of different values of hunger nodes determination threshold C_{th} to network goodput. Note that the network goodput basically decreases as C_{th} increases. It can be understood from the figure that lower C_{th} results in more nodes becoming hunger nodes thus improving the overall network goodput due to their attempts to take part in the concurrent transmission under a lower threshold. However, after 220 seconds in this simulation, the network goodput for $C_{th} = 1$ is lower than $C_{th} = 3$ and the gap between two curves seems to be bigger along with the simulation time increasing. This is because setting C_{th} to 1 actually overestimates the network hunger level and is not the optimal value for this simulation scenario. How-

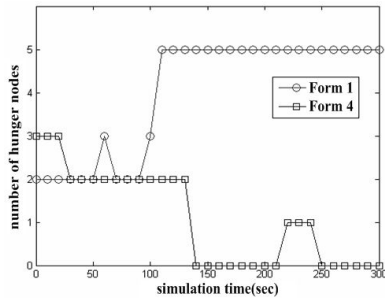


Fig. 12 Number of hunger nodes versus simulation time with different price formulas.

ever, $C_{th} = 3$ shows a relatively stable relation with network goodput and could be a better choice.

Figure 12 shows the performance comparison of hunger nodes suppression capability between Form 1 and Form 4. It can be seen that the results of form 1 are greatly worse than form 4 in most of simulation time. The reason is that there is no any consideration for hunger nodes restraining in form 1. A short falling time around 30~50 and 70~90 seconds for form 1 are due to the instantaneously good channel quality during both periods. We also have observed that a severe network partitioning occurred after 110 seconds in form 1 due to large number of hunger nodes appearing on the boundary of partitions. Further, network partition in turn will aggravate the hunger level resulting in the worse case. However, with Form 4, although there are 2 hunger nodes appears at first, the number of hunger nodes drop to 0 with more hungers taking part in relay forwarding. Similar to form 1, the fluctuation around 220-240 seconds is due to the instantaneously bad channel quality.

8. Conclusion

In this paper, we have proposed a decentralized concurrent transmission game with channel quality considered in a shared channel. By verifying the feasibility of this game, we further present examples for solving the Nash Equilibrium. The hunger problem caused by threshold-based concurrent transmission determination has also been investigated by setting proper price formula to reserve interferences for hunger nodes. To handle the inaccurate results due to lack of global knowledge of the entire work, such as overestimation or underestimation of concurrent transmission thresholds in game, a relay incentive price expression is introduced. Numerical results show the proposed approach is feasible and suitable for concurrent transmission in Ad Hoc networks and has better performance.

In summary, for Ad Hoc networks typically with fluctuant channel qualities, using channel gains based game is economic and convenient for providing distributed concurrent transmission determination. We hope that this work would help those who are working on the improvement of network goodput, especially in Ad Hoc networks.

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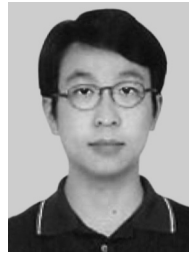
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