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Cooperative Game Based Traffic Control Scheme for the Dual-channel CAN Platform

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ABSTRACT In recent years, automotive manufactures have installed dozens of electronic controller units (ECUs) for various functions related to safety and convenience of drivers. Each ECU controls specific functions of a vehicle, and exchanges information by using the controller area network (CAN). It is characterized by low cost, efficient communication, and high flexibility. In this work, we aim to study the property of CAN bus, and design a new traffic control algorithm to get an excellent CAN system performance. By employing the concepts of two different cooperative game solutions, our approach explores the impact of ECUs' mutual-interaction relationship and devises a novel two-step game model to take the full advantages of CAN resource sharing process. To adaptively handle different data service requirements, control decisions in our two-step game are mutually dependent each other, and each individual ECU acts cooperatively in the proper collaboration manner. This interactive coordinated process continues until a desirable solution is obtained; it is a practical and suitable approach in real world CAN system operations. Finally, simulation testbed is constructed and the numerical analysis is conducted to demonstrate the performance improvement of our proposed method. In addition, several research challenges are discussed and open issues are also outlined.

INDEX TERMS Controller area network, electronic controller units, cooperative game theory, minimax regret bargaining, relative benefit equilibrating.

I. INTRODUCTION

Automotive vehicle systems have been developed with complexity due to ever-increasing adoption of electronics including engine management, ignition, radio, carputers, telematics, in-car entertainment systems, and electronic controller units (ECUs). An ECU is a small device in a vehicle's body that is responsible for controlling a specific function. Today's vehicles may contain multiple ECUs with different controlling functions that range from the essential control to comfort features. Each ECU requires power and data connections to operate. Usually, individual ECUs receive inputs from different parts of the vehicle, depending on their function. In recent years, an intelligent system has been adopted to process more data exchanges between ECUs while reducing the wire cost. There are many ECU communication standards, such as the FlexRay, local interconnected network, automotive Ethernet, in-vehicle network and controller area network (CAN) [1], [2].

Originally, the CAN was developed by BOSCH as a multi-master, event-triggered, serial communication bus protocol to support bus speeds of up to 1 Mbit/s. Unlike a traditional network such as Ethernet, the CAN does not send large blocks of data in the point-to-point mode. In a CAN network, many short messages are broadcast to the entire network, which provides for data consistency in every ECUs of the in-vehicle system. Among several protocols enabling ECUs to communicate in the real-time network protocol, the CAN protocol is undoubtedly really stable, well known, and the most widely used in the automotive domain. In 2003, the International Organization for Standardization (ISO) standardized CAN in ISO 11898-1. Over 30 years, the reliability and simple network structure of the CAN protocol have made it a de-facto standard for ECU communications [3], [4].

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Recently, a novel effective CAN network system has been developed [5]–[7]. It supports data rates ranging from 20 kb/s to 1 Mb/s with multiple agents, and the CAN transmitter of each agent is connected to the common bus line, which has the limited bandwidth. Despite the advantages of the CAN protocol, it was not designed with fair-efficiency features in mind. Therefore, the in-vehicle CAN network is open to attack from the bandwidth unfair-sharing problem. Usually, data generated from distributed ECUs are classified into two classes: class I (real-time data) and class II (non real-time data) according to the delay sensitivity. In the CAN bus, these data share a common network medium. In this circumstance, transmission of class I data could be interfered by class II data, and the network-induced delay of class I data could exceed a predefined delay limit. This may cause the performance inefficiency and instability of real-time application systems. Therefore, it is necessary to guarantee the real-time requirements while increasing the CAN system capacity [5]–[7].

As an alternative to increasing the CAN system's capacity and performance, dual-channel CAN bus platform has been introduced [4]–[7],[12]. Recently, several off-the-shelf microcontrollers have been developed with two communication bus channels. It becomes an universal solution to match almost CAN applications while exchanging different data among ECUs in the CAN. To achieve efficient operations in the dual-channel CAN system, autonomous, distributed, and rational ECUs should work together and act cooperatively with each other to enhance conflicting performance criteria. Therefore, the main goal to design a new dual-channel CAN control scheme is to guide rational and strategic ECUs' decisions toward their effective cooperation and consensus through fair-efficiently sharing the limited CAN bandwidth. However, it is an extremely challenging and difficult work. Therefore, we need a new intelligent control paradigm and novel solution concept [7].

The control scenario of dual-channel CAN system may fall into cooperative game theory. Therefore, we propose looking at the traffic control problem of dual-channel CAN system through the lens of cooperative game theory. Originally, John Nash proposed an new idea of cooperative games in the 1950s. His idea is based on the intuition that if some game players have better outside options than others, the net surplus will be divided equally. Since then, various economists and scientists have extended the Nash's idea to various control fields. In different game settings, each player has a set of potential contracts, and the outside options of cooperative consensus are endogenous to the game model. In cooperative games, sets of game players are mapped to values representing the surplus they alone can generate, and game solution assigns a payoff to each player. Therefore, solution concepts are at the heart of cooperative game theory. Until now, the research literature has a rich history exploring various cooperative game's solution concepts, their axiomatic properties, and computability [8].

A. TECHNICAL CONCEPTS

In 2001, W. Bossert and H. Peters propose a new solution concept of cooperative game, called the *minimax regret and efficient bargaining solution* (later abbreviated as *MREBS*). And then, they characterize the *MREBS*, which generate ex ante efficient combinations of outcomes under the assumption that the game players have minimax regret preferences. Usually, monotone utopian bargaining solutions are characterized by the efficiency criterion with respect to the max-min criterion. According to this criterion, the minimal gains with respect to the disagreement point should be maximized. Originally, the *MREBS* is developed by considering the minimax regret criterion, where regret is measured with respect to the utopia payoffs, i.e., the maximal attainable payoffs. By incorporating scale covariance into the minimax regret preferences, the idea of *MREBS* can be applicable for the general case cooperative games while including the concept of *Raiffa-Kalai-Smorodinsky* bargaining solution [9].

In 2017, M. Radzvilas proposes the *relative benefit equilibrating bargaining solution* (later abbreviated as *RBEBS*), which is developed based on comparisons of game players' ordinal relative individual benefit gains. Usually, cooperative game solutions are based on assumption that game players care not only about their absolute individual benefit gains associated with a particular agreement, but also about how that agreement is reached, and how the benefits of an agreement are distributed among them. In real-world cooperative games, an agreement can realistically be reached only if at least one of game players makes a concession. Each of the feasible agreements is associated with a specific combination of concessions that game players would have to make in order to reach an agreement. Therefore, it seems natural to expect game players aiming to find an agreement with the most equitable distribution of concessions. Following this line of thought, the *RBEBS* arbitrates the relationship between the measurement procedure for ordinal relative individual advantage gains and the measurement procedure for players' ordinal relative concessions. Even though the *RBEBS* does not satisfy the symmetry axioms in purely ordinal games, it satisfies a number of axioms which, at least intuitively, should be satisfied by any credible ordinal bargaining solution [10].

B. MAIN CONTRIBUTIONS

According to the *MREBS* and *RBEBS*, we can effectively handle the traffic control problem in the dual-channel CAN system. First, the traffic amount for each ECU is decided by using the idea of *MREBS*. Under dynamic and diverse CAN traffic environments, each individual ECU makes decisions to reach a mutually acceptable agreement. Second, the assigned traffic of each ECU is adaptively distributed into the dual communication channels in a coordinated manner. Based on the current traffic status, each channel has a different feature. By using the step-by-step interactive cooperative process, the proposed algorithm is designed as a repeated bargaining game model to dynamically share the limited CAN bandwidth resource. Therefore, our two-step cooperative game based approach is flexible, adaptable and able to sense the dynamic changing CAN traffic environment. This feature leads to a balance appropriate system performance. In detail, the major contributions of this study are summarized as;

- This study investigates the ideas of cooperative game theory to design our CAN system traffic control scheme. By considering the dual-channel infrastructure, we formulate our scheme as a two-step cooperative game model to achieve a mutually desirable solution.
- At the first-step game model, the idea of *MREBS* is used to compromise the conflicting views of different ECUs. Through the approach of minimax regret preferences, cooperative interactions among ECUs result in a fair-efficient bandwidth sharing solution.
- At the second-step game model, each individual ECU distributes its assigned traffic amount into the dual CAN channels based on the concept of *RBEBS*. Through the arbitration between the relative advantage gains and concession, we can attain a globally desirable solution for the dual channel operations.
- We explore the interaction of different bargaining solutions while leveraging the synergistic features. Based on the combination of *MREBS* and *RBEBS*, the main challenge of our proposed scheme is to get a reciprocal consensus among individual ECUs.
- We provide simulation results to verify the correctness and the potential benefits of our proposed approach compared with existing CAN traffic protocols. Through experimental measurements, we can confirm that our two-step cooperative game model can lead to a better CAN system performance.

C. ORGANIZATION

The rest of the paper is organized as follows. Section II describes the related work about the CAN traffic control issue. In Section III, we introduce the background knowledge of the dual-line CAN infrastructure, and the fundamental concepts of *MREBS* and *RBEBS*. And then, some details are provided about our new two-step cooperative game model. To increase readability, the main steps of our proposed algorithm are given. Section IV contains a performance evaluation. It shows the accuracy and advantages of our proposed method by comparing the existing protocols. Finally, Section V draws some concluding remarks.

II. RELATED WORK

This section presents a brief review of some related work about the CAN protocols. Most existing CAN researches generally pay attention to the electromagnetic simulation, integrated circuit design, and signal integrity analysis. To address traffic control problems in the CAN platform, few literature papers have been published. The paper [11] presents a delay-tolerant predictive power compensation control for voltage regulation in distribution feeders. After estimating the maximum tolerable communication delay based on voltage and power mutation, it uses normal power compensation control for effective operations when communication delay is within the maximum tolerable communication delay, or switches to predictive power compensation control under abnormal communication delay conditions. An accurate prediction is achieved using a double neural network with on-line adjustment of weights and samples [11]. In [12], a new dual redundancy CAN-bus controller is designed based on the field programmable gate array (FPGA). By downloading the IP Core into a XILINX's SPARTAN-3 chip to test, it is successfully implemented; the new design could completely meet the requirement for high real-time performance and reliability [12]. S. Mubeen *et al.* propose the *Queue based Mixed Message Control* (*QMMC*) scheme by using the response-time analysis (RTA) [4]. The RTA is a powerful, mature and well established schedule analysis technique, and it can calculate upper bounds on the response times of tasks or messages in a real-time system or a real-time network respectively. The motivation for this work comes from the industrial requirements and the activity of implementing the holistic response-time analysis The *QMMC* scheme supports the RTA of mixed message transmission patterns. These type of messages are implemented in the automotive industry. Moreover, this scheme extends the existing analysis for CAN with FIFO queues by integrating it with the analysis for mixed messages in CAN with priority queues. Therefore, the *QMMC* scheme is able to calculate the worst-case response times of periodic, sporadic and mixed CAN messages in networks where some nodes implement priority queues while others implement FIFO queues. Finally, the paper [4] conducts a case study and the comparative evaluation with existing analysis for mixed, periodic and sporadic messages in CAN with priority queues.

The *Real Time Bandwidth Allocation* (*RTBA*) scheme is introduced as a bandwidth allocation algorithm for the CAN bus [5]. This scheme can be effectively utilized in the design and implementation phase of distributed real-time control and automation systems that use CAN protocol. In this paper, data generated from process control agents in manufacturing automation are classified into three categories; real-time event data, real-time control data, and non real-time data. In each vehicle, agents in a control loop periodically generate their real-time data according to a sampling interval, and these data should be transferred within the delay deadline. However, non real-time data, such as program data files and database management information, can be tolerate the delay compared to that of real-time data. These data share the common CAN bandwidth. The *RTBA* scheme satisfies the delay requirement of the real-time data while maximizing the utilization of bandwidth by fully exploring the residual bandwidth resource. Finally, this approach is validated by using the simulation model that integrates the discrete-event model of the CAN protocol and the continuous-time model of a feedback control system [5].

In [6], a new CAN control algorithm, called the *Delay Compensation Controller Control* (*DCCC*) scheme, is introduced for vehicle network control systems. This approach considers uncertain discrete-time systems over CAN networks, and proposes a new feedback control mechanism with the aid of a time-domain Smith predictor, which can predict the non-delayed states. Due to the main features of Smith predictor, the maximal tolerable delay will drastically increase although the stability criterion is relatively conservative. With the predicted states and the delay information, the a new delay compensation algorithm is developed with CAN buses and a relatively simple Lyapunov function. If the system model is accurate without any uncertainty, the effect of the delay can be completely eliminated. With the simulation results, authors demonstrate that the *DCCC* scheme is effective in the electronic throttle control over a CAN bus [6].

The existing methods [4]–[6], [11]–[12] have studied the traffic control problem to improve the performance of CAN protocol. However, none of the researches in the literature consider the cooperative game approach from an interactive perspective. Therefore, they can't get mutual advantages based on the different control viewpoint of each vehicle agent. Only our proposed two-step cooperative game approach can provide a fair-efficient traffic control solution while fully utilizing the limited CAN system.

III. THE PROPOSED SCHEME FOR INTER-ISP CONTROL ISSUES

In this section, we present the CAN system platform that characterizes the properties of the dual communication channel infrastructure. Then, we introduce the fundamental concepts of *MREBS* and *RBEBS* to design our two-step bargaining game model. Finally, the main step procedures of our proposed CAN traffic control algorithm are delineated to help readers' comprehension.

A. DUAL CHANNEL CAN SYSTEM INFRASTRUCTURE

In this paper, we consider a dual-channel CAN platform, which consists of two communication channels to reduce the traffic overhead. Theses buses can be accessed by individual ECUs at each time. Generally, there are class I and class II data transmitted on these buses. Therefore, there will be cases in which two or more ECUs are trying to occupy the bus simultaneously. In such cases, the bus access is implemented with an adaptive arbitration process. The arbitration is implemented through the data priority, and the limited bandwidth is dynamically allocated based on the traffic preferences. Let $\mathbb{N} = \{\mathcal{N}_1, \ldots, \mathcal{N}_n\}$ be the set of ECUs and $\mathcal{L}_f$, $\mathcal{L}_s$ are the first and second bus lines, respectively. ECUs in $\mathbb{N}$ are interconnected together, and exchange information between themselves through $\mathcal{L}_f$ and $\mathcal{L}_s$. $\mathfrak{M}_f$ and $\mathfrak{M}_s$ are bandwidth capacities for the $\mathcal{L}_f$ and $\mathcal{L}_s$, respectively.

We consider a discrete time model $T \in \{t_1, \ldots, t_c, t_{c+1}, \ldots\}$, where the length of a time slot matches the event time-scale at which our communication control decisions are updated. In this study, we formulate the ECUs' interaction process as the upper-level cooperative game $\left(\mathbb{G}^U\right)$, and each individual $\mathcal{N}_{1\leq i\leq n}$ gets its assigned bandwidth $\left(\Theta_{\mathcal{N}_i}\right)$ through the concept of *MREBS*. Therefore, the $\mathcal{N}_i$ has a right to transfer his data within the $\Theta_{\mathcal{N}_i}$'s acceptable limit. Since then, the $\mathcal{N}_i$ distributes its traffic amount, which is not larger than the $\Theta_{\mathcal{N}_i}$, into the $\mathcal{L}_f$ and $\mathcal{L}_s$ by using the idea of *RBEBS*. This process is modeled as the lower-level cooperative game $\left(\mathbb{G}^L_{\mathcal{N}_i}\right)$. $\mathbb{G}^U$ and $\mathbb{G}^L_{\mathcal{N}_i}$ are repeated sequentially in a slotted time structure. Based on the interactive feedback manner, our CAN traffic control scheme is operated each time period during the step-by-step iteration. To reduce computation complexity, in the proposed scheme, the amount of bandwidth allocation is specified in terms of basic bandwidth units (BBUs). Formally, we define game entities for the dual-channel CAN system infrastructure, i.e, $\left\{\mathbb{G}^U, \mathbb{G}^L_{\mathcal{N}_{1\leq i\leq n}}\right\} = \{\mathbb{N}, \{\mathcal{L}_f, \mathcal{L}_s\}, \{\mathfrak{M}_T | \mathfrak{M}_f, \mathfrak{M}_s\}, \mathcal{B}_u, \{\mathcal{N}_i \in \mathbb{N} | U^U_{\mathcal{N}_i}, U^{\mathcal{L}_f}_{\mathcal{N}_i}, U^{\mathcal{L}_s}_{\mathcal{N}_i}, \mathcal{Q}_{\mathcal{N}_i}, \Theta_{\mathcal{N}_i}\}, T\}$ of gameplay, and Table 1 lists the notations used in this paper.

- $\mathbb{G}^U$ and $\mathbb{G}^L_{\mathcal{N}_i}$ are upper and lower cooperative game models; they are related in a coordination manner of mutual and reciprocal interdependency.

TABLE 1. The notations for abbreviations, symbols and parameters.

Acronym	Explanations
CAN	controller area network
ECUs	electronic controller units
ISO	International Organization for Standardization
MREBS	*minimax regret and efficient bargaining solution*
RBEBS	*relative benefit equilibrating bargaining solution*
QMMC	*Queue based Mixed Message Control*
RTA	response-time analysis
RTBA	*Real Time Bandwidth Allocation*
DCCC	*Delay Compensation Controller Control*
BBUs	basic bandwidth units
P	Pareto optimal
Notations	**Explanations**
$\mathbb{N}$	the set of ECUs
$\mathcal{N}_{1\leq i\leq n}$	individual ECU
$\mathcal{L}_f, \mathcal{L}_s$	the first and second bus lines
$\mathfrak{M}_f$,$\mathfrak{M}_s$	bandwidth capacities for the $\mathcal{L}_f$ and $\mathcal{L}_s$
$\mathbb{G}^U$	the upper-level cooperative game
$\Theta_{\mathcal{N}}$	the assigned bandwidth of each $\mathcal{N}$
$\mathbb{G}^L_{\mathcal{N}}$	the lower-level cooperative game
$\mathfrak{M}_T$	he total CAN system bandwidth capacity
$\mathcal{B}_u$	a BBU to allocate the bus link bandwidth
$U^U_{\mathcal{N}}$	utility function of $\mathcal{N}$ at the $\mathbb{G}^U$
$U^{\mathcal{L}}_{\mathcal{N}}$	utility function of $\mathcal{L}$ at the $\mathbb{G}^L_{\mathcal{N}}$
$\mathcal{Q}_{\mathcal{N}}$	$\mathcal{N}$'s generated data amount
$\Theta_{\mathcal{N}}$	assigned bandwidth to the $\mathcal{N}$
$\boldsymbol{N}$	a finite set of cooperative game players
$\mathbb{R}^n$	the *n*-fold Cartesian product of real number
S	feasible outcomes in cooperative game
d	disagreement point
γ , η	class I data coefficient factors
σ, α, β	class II data coefficient factors
$\Upsilon^t_{\mathcal{N}}$	$\mathcal{N}$'s distributed data amount
$\chi^{\mathcal{L}}_{\mathcal{N}}$	The ratio of $\Upsilon^t_{\mathcal{N}}$'s division for $\mathcal{L}$
ω, ξ, ε	coefficient factors for the class I service
τ, ψ	coefficient factors for the class II service

- $\mathbb{N}$ is the set of the set of ECUs $\left(\mathcal{N}_{1\leq i\leq n}\right)$, and they are game players in the $\mathbb{G}^U$.
- $\mathcal{L}_f$ and $\mathcal{L}_s$ are the first and second bus lines, respectively, and they are game players in the $\mathbb{G}^L_{\mathcal{N}_i}$.
- $\mathfrak{M}_T$ is the total CAN system bandwidth capacity. $\mathfrak{M}_f$ and $\mathfrak{M}_s$ are bandwidth amounts for the $\mathcal{L}_f$ and $\mathcal{L}_s$, respectively, where $\mathfrak{M}_T = \mathfrak{M}_f + \mathfrak{M}_s$.
- $\mathcal{B}_u$ is a basic bandwidth unit to allocate the bus link bandwidth.
- $U^U_{\mathcal{N}_i}$ is the utility function of $\mathcal{N}_i$ at the $\mathbb{G}^U$.
- At the $\mathbb{G}^L_{\mathcal{N}_i}$, $U^{\mathcal{L}_f}_{\mathcal{N}_i}$ is the utility function of $\mathcal{L}_f$ and $U^{\mathcal{L}_s}_{\mathcal{N}_i}$, is the utility function of $\mathcal{L}_s$.
- $\mathcal{Q}_{\mathcal{N}_i}$ is the $\mathcal{N}_i$'s generated data amount, and $\Theta_{\mathcal{N}_i}$ is the assigned bandwidth to the $\mathcal{N}_i$. Therefore, $\mathbf{min}\left(\mathcal{Q}_{\mathcal{N}_i}, \Theta_{\mathcal{N}_i}\right)$ is the traffic amount, which is distributed into the $\mathcal{L}_f$ and $\mathcal{L}_s$.
- $T = \{t_1, \ldots, t_c, t_{c+1}, \ldots\}$ denotes time, which is represented by a sequence of time steps.

B. THE BASIC CONCEPTS OF MREBS AND RBEBS

Usually, a cooperative game solution assigns a feasible utility tuple to every bargaining problem. Therefore, it aggregates the individual preferences of game players into a collective outcome. In more technical terms, each player has a criterion to decide between several contingent contracts. To implement a new view on cooperative game solutions, we adopt the ideas of *MREBS* and *RBEBS*. To explain these bargaining solutions, we introduce the notation and basic definitions. Denote $\boldsymbol{N} = \{1, \ldots, n\}$ be a finite set of cooperative game players. Let $\mathbb{R}^n$ be the n-fold Cartesian product of real number set $\mathbb{R}$, and the set of all nonnegative vectors in $\mathbb{R}^n$ is denoted by $\mathbb{R}^n_+$. An n-player cooperative game has a solution set $S \subset \mathbb{R}^n$ where elements of S are called feasible outcomes. If game players fail to reach some other outcome $x \in S$, a disagreement point $d = \{d_1 \ldots d_n\}$ results where $d \in S \subset \left(d + \mathbb{R}^n_+\right)$; S contains a vector $x > d$ for all $x \in S$. For any two vectors $x, y \in \mathbb{R}^n, x > (or \geq) y$ means $x_{1\leq i\leq n} > (or \geq) y_{1\leq i\leq n}$. The inequalities $<$ and $\leq$ are defined analogously [9].

Denote $\mathbb{C}$ as the class of all n-player cooperative game, and a game solution is a mapping $\mathcal{F} : \mathbb{C} \rightarrow \mathbb{R}^n$ with $\mathcal{F}(S) \in S$ for all $S \in \mathbb{C}$. A solution $\mathcal{F}$ is called *Pareto optimal* if $\mathcal{F}(S) \in \boldsymbol{P}(S)$ for all $S \in \mathbb{C}$ where $\boldsymbol{P}(S) = \{x \in S | \forall y \in S\, [y \geq x \Rightarrow y = x]\}$. In S, each player i has a transitive and reflexive preference relation $\succeq_i$; $x \succ_i y$ means $x_i > y_i$, where $\succ_i$ denotes the asymmetric part of $\succeq_i$. Let $\mathcal{F}$ and $\succeq$ be a cooperative game solution and $\left(\succeq_1, \ldots, \succ_n\right)$, respectively, and $\mathcal{F}$ is called to be *efficient with respect to* $\succeq_i$ if there is a player i with $\mathcal{F}(S) \succeq_i$ for all $S \in \mathbb{C}$ and all $x \in S$. Finally, *efficiency with respect to* $\succeq_i$ implies *Pareto optimality*. A solution $\mathcal{F}$ is called *scale covariant* if $(a \cdot \mathcal{F}(S) + b) = \mathcal{F}(a \cdot S + b)$ for all $a, b \in \mathbb{R}^n$. With the *scale covariant* property, the player i's minimax regret preference may be normalized to a preference $\widetilde{\succeq_i^u}$ as follows [9];

$$x \widetilde{\succeq_i^u} y \equiv \mathbf{max}\left\{\frac{u_i(S) - x_i}{u_i(S) - d_i(S)}\right\} \leq \mathbf{max}\left\{\frac{u_i(S) - y_i}{u_i(S) - d_i(S)}\right\}$$
$$\text{s.t., } u_{1\leq i\leq n}(S) := \max_{x\in S} x_{1\leq i\leq n}, \;\; S \in \mathbb{C}, \text{ and } x, y \in S \tag{1}$$

where $u(S)$ is an utopia point of a problem $S \in \mathbb{C}$. Formally, the *MREBS* is defined as follows;

$$MREBS\,(S, d)_x = \left(\boldsymbol{P}(S) \cap \left\{u(S) | x \widetilde{\succeq_i}^u_i y\right\}\right) \geq d \tag{2}$$

The other bargaining solution, the *RBEBS*, recommends a implementation of a feasible agreement which minimizes the difference between players' relative concessions. To simply explain the concept of *RBEBS*, we assume that there are only two game players where $\boldsymbol{N} = \{1, 2\}$. Each agreement $x_i \in S$ is a pair of demands $x_i = (g_1, g_2)$ over some amount of divisible resource, the total amount of which is $\mathfrak{P}$. Each demand g_i of every $i \in \boldsymbol{N}$ is selected from the interval $[d_i, \ldots, \mathfrak{P}]$. Let $\mathcal{S} \subseteq \mathcal{A}$ be a subset of feasible agreements of $\mathbb{C}$. For any pair $x_i = (g_1, g_2) \in \mathcal{S}$ and $x_{j\neq i} = (h_1, h_2) \in \mathcal{S}$, such that $h_i > g_i$, the preferences of i are such that $h_i \succ_i g_i$, and so $x_j \succ_i x_i$. Since every $x_i \in \mathcal{S}$ is such that $g_1 + g_2 \in \mathcal{S}$, each player i has a strict preference relation $\succ_i$ over $\mathcal{S} \subseteq S$. For each i, the cardinality of the preferred set of agreements associated with some feasible agreement $x_i \in \mathcal{S}$ can be defined as follows [10];

$$\begin{aligned}
&c_i\left(x_i, \{\mathcal{S}, d\}\right) \\
&\quad = \left\{|T|, \text{where } x_{j\neq i} \in T \Rightarrow \left(\left(x_j \in \{\mathcal{S}, d\}\right)\left(x_j \succ x_i\right)\right)\right\} \\
&\qquad \text{s.t., } \mathcal{S} = \{x_i = (g_1, g_2) \in \mathcal{S} : (g_1 + g_2 = \mathfrak{P}) \\
&\qquad \wedge \left(x_{i \succeq_i} d\right), \forall i \in \boldsymbol{N}\}
\end{aligned} \tag{3}$$

From (3), it follows that $x_{j\neq i} \succ_i x_i$ if and only if $c_j\left(x_j, \{\mathcal{S}, d\}\right) < \mathrm{c}_i\left(x_i, \{\mathcal{S}, d\}\right)$. We can assume that each player's cardinality can be interpreted as a measure of the size of player's concession. Commonsensically, each rational player seeks an implementation of an agreement which minimizes the cardinality of the preferred set of alternatives. Let $c_i^{max}\left(\{\mathcal{S}, d\}\right)$ and $c_i^{min}\left(\{\mathcal{S}, d\}\right)$ be the player i's maximum and minimum possible concession associated with some outcome in the set $\{\mathcal{S}, d\}$, respectively. Since, $x_i \succ_i d_i \forall x_i \in \mathcal{S}$, it follows that $c_i^{max}\left(\{\mathcal{S}, d\}\right) = c_i(d)$ and $c_i^{min}\left(\{\mathcal{S}, d\}\right) = 0$. Therefore, the player i's relative concession associated with some feasible outcome $y_i \in \{S, d\}$, i.e., $\mathcal{R}^{y_i}\left(y_i, \{S, d\}\right) \in [0, 1]$, can be defined as follows [10]:

$$\mathcal{R}^{y_i}\left(y_i, \{S, d\}\right) = \frac{c_i^{min}\left(\{S, d\}\right) - c_i\left(y_i, \{S, d\}\right)}{c_i^{min}\left(\{S, d\}\right) - c_i^{max}\left(\{S, d\}\right)}$$
$$\text{s.t., } \begin{cases} c_i^{max}\left(\{\mathcal{S}, d\}\right) := \underset{x_i \in \{\mathcal{S}, d\}}{\mathbf{argmax}}\left[c_i\left(x_i, \{\mathcal{S}, d\}\right)\right] \\ c_i^{min}\left(\{\mathcal{S}, d\}\right) := \underset{x_i \in \{\mathcal{S}, d\}}{\mathbf{argmin}}\left[c_i\left(x_i, \{\mathcal{S}, d\}\right)\right] \end{cases} \tag{4}$$

Since $c_i^{min}(\{S,d\}) = 0$ and $c_i^{max}(\{S,d\}) = c_i(d)$, $\mathcal{R}^{y_i}(y_i,\{S,d\})$ can be simplified as follows:

$$\mathcal{R}^{y_i}(y_i,\{S,d\}) = \frac{-c_i(y_i,\{S,d\})}{-c_i(d)} = \frac{c_i(y_i,\{S,d\})}{c_i(d)} \quad (5) \tag{5}$$

Since the player i's individual benefit gain represents the number of total possible concessions that he does not make if outcome $y \in \{S,d\}$ obtains, the player i's relative individual benefit gain associated with $y_i \in \{S,d\}$, i.e., $\mathcal{G}^{y_i}(y_i,\{S,d\}) \in [0,1]$, can be defined as follows [10]:

$$\mathcal{G}^{y_i}(y_i,\{S,d\}) = \frac{c_i^{max}(\{S,d\}) - c_i(y,\{S,d\})}{c_i^{max}(\{S,d\}) - c_i^{min}(\{S,d\})} \tag{6}$$

Since $c_i^{min}(\{S,d\}) = 0$ and $c_i^{max}(\{S,d\}) = c_i(d)$ for the player i, $\mathcal{G}^{y_i}(y_i,\{S,d\})$ can be simplified as follows [10]:

$$\mathcal{G}^{y_i}(y_i,\{S,d\}) = \frac{c_i(d) - c_i(y_i,\{S,d\})}{c_i(d)} \quad (7) \tag{7}$$

Finally, the *RBEBS* can be defined with in terms of relative concessions [10]:

$$\begin{aligned} &RBEBS(S,d)_x \\ &= \mathop{\mathbf{arg\,min}}_{x_i \in S} \left[\left|\left(\mathcal{G}^{x_i}(x_i,\{S,d\}) - \mathcal{G}^{x_{j\neq i}}(x_i,\{S,d\})\right)\right|\right] \\ &= \mathop{\mathbf{arg\,min}}_{x_i \in S} \left[\left|\left(1 - \mathcal{R}^{x_i}(x_i,\{S,d\})\right) - \left(1 - \mathcal{R}^{x_{j\neq i}}(x_i,\{S,d\})\right)\right|\right] \\ &= \mathop{\mathbf{arg\,min}}_{x_i \in S} \left[\left|\mathcal{R}^{x_i}(x_i,\{S,d\}) - \mathcal{R}^{x_{j\neq i}}\left(x_j,\{S,d\}\right)\right|\right] \\ &\quad \text{s.t., } \mathcal{G}^{x_i}(x_i,\{S,d\}) = 1 - \frac{c_i(x_i,\{S,d\})}{c_i(d)} \\ &= 1 - \mathcal{R}^{x_i}(x_i,\{S,d\}), \quad \forall x_i \in S \end{aligned} \tag{8}$$

C. THE TWO-STEP COOPERATIVE GAME MODEL FOR THE CAN SYSTEM

Each ECU $\left(\mathcal{N}_{1\leq i\leq n}\right)$ is connected to the two CAN bus channels, and two type data are generated probabilistically. In the class I and class II data, service priority is differently decided. In our CAN traffic control scheme, we first assign the bus bandwidth ($\mathfrak{M}_T$) for individual ECUs at each time slot; it can effectively restrict the total traffic amount of ECUs. And then, the ECUs' data are distributed into two channels. Theoretically, if two channels are used in the CAN platform, it should be possible to reduce the traffic on each channel to half [7]. However, under a dynamically changing CAN traffic environment, it is difficult to create an ideal condition to provide the fair-efficient traffic distribution. In this study, the bandwidth assignment problem is formulated in the $\mathbb{G}^U$, and each ECU's traffic distribution problem is modelled in the $\mathbb{G}^L_{\mathcal{N}}$. At the $\mathbb{G}^U$, $\mathcal{N}_{1\leq i\leq n}$, are game players, and the utility function of $\mathcal{N}_i$ at time t_c, i.e., is defined as $U^U_{\mathcal{N}_i}(\cdot)$. This function has been formally onwards and upwards according to the assigned bandwidth amount. Therefore, it is mathematically defined as follows (9), as shown at the bottom of the next page, where $\mathcal{Q}^{t_c}_{\mathcal{N}_i}$ is the $\mathcal{N}_i$'s generated data amount, and $\Theta^{t_c}_{\mathcal{N}_i}$ is the assigned bandwidth to the $\mathcal{N}_i$ at time t_c. For the class I data service, γ is a coefficient factor and η is an adjustment parameter. For the class II data service, σ, α are coefficient factors, and β is an adjustment parameter. η and β values are dynamically decided based on the data preferences. In the $\mathbb{G}^U$, the $\mathfrak{M}_T$ is adaptively allocated to individual $\mathcal{N}_{1\leq i\leq n}$ according to the *MREBS*.

$$\begin{aligned} &MREBS_{\mathbb{X}=\left\{\Theta^{t_c}_{\mathcal{N}_1},\ldots,\Theta^{t_c}_{\mathcal{N}_n}\right\}}\left(\mathbb{U} = \left\{\ldots U^U_{\mathcal{N}_{1\leq i\leq n}}(\cdot)\ldots\right\},\right. \\ &\left.\mathbb{D} = \left\{\ldots d_{\mathcal{N}_i}\ldots\right\}\right) \\ &= \left(\max\left\{\frac{\mathbb{U}_{\mathcal{N}_i}(\mathbb{X}) - U^U_{\mathcal{N}_i}\left(\mathcal{Q}^{t_c}_{\mathcal{N}_i},\Theta^{t_c}_{\mathcal{N}_i},\eta,\beta\right)}{\mathbb{U}_{\mathcal{N}_i}(\mathbb{X}) - \mathbb{D}_{\mathcal{N}_i}(\mathbb{X})}\right\}\right. \\ &\left.\leq \max\left\{\frac{\mathbb{U}_{\mathcal{N}_i}(\mathbb{X}) - U^U_{\mathcal{N}_i}\left(\mathcal{Q}^{t_c}_{\mathcal{N}_i},\Theta^{t_c}_{\mathcal{N}_i},\eta,\beta\right)}{\mathbb{U}_{\mathcal{N}_i}(\mathbb{X}) - \mathbb{D}_{\mathcal{N}_i}(\mathbb{X})}\right\}\right) \\ &\quad \text{s.t., } \mathbb{U}_{\mathcal{N}_{1\leq i\leq n}}(\mathbb{X}) := \max_{\Theta^{t_c}_{\mathcal{N}_i}\in\mathbb{X}} U^U_{\mathcal{N}_i}\left(\mathcal{Q}^{t_c}_{\mathcal{N}_i},\Theta^{t_c}_{\mathcal{N}_i},\eta,\beta\right), \\ &\quad \Theta^{t_c}_{\mathcal{N}_i} \neq \Theta'^{t_c}_{\mathcal{N}_i} \text{and } \mathfrak{M}_T \geq \sum_{\mathcal{N}_i\in\mathbb{N}} \Theta^{t_c}_{\mathcal{N}_i} \end{aligned} \tag{10}$$

The $\mathcal{N}_i$ gets the $\Theta^{t_c}_{\mathcal{N}_i}$ in the $\mathbb{G}^U$, and then the $\mathcal{N}_i$ distributes its data amount $\Upsilon^{t_c}_{\mathcal{N}_i}$ into two channels, i.e., $\mathcal{L}_f$ and $\mathcal{L}_s$, at time t_c where $\Upsilon^{t_c}_{\mathcal{N}_i} = \mathbf{min}\left(\mathcal{Q}^{t_c}_{\mathcal{N}_i},\Theta^{t_c}_{\mathcal{N}_i}\right)$. In the $\mathbb{G}^L_{\mathcal{N}_i}$, the $\mathcal{N}_i$ attempts to smooth out the traffic overhead between $\mathcal{L}_f$ and $\mathcal{L}_s$; they have different traffic conditions based on the data service priorities. In the proposed scheme, each $\mathcal{N}$ operates individually its lower level cooperative game ($\mathbb{G}^L_{\mathcal{N}}$) to maximize the CAN system performance in a collaborative manner. In the $\mathbb{G}^L_{\mathcal{N}_i}$, $\mathcal{L}_f$ and $\mathcal{L}_s$ are game players, and the $\mathcal{L}_f$'s utility function, i.e., $U^{\mathcal{L}_f}_{\mathcal{N}_i}$, is defined as follows;

$$\begin{aligned} &U^{\mathcal{L}_f}_{\mathcal{N}_i}\left(\chi^{\mathcal{L}_f}_{\mathcal{N}_i},\Upsilon^{t_c}_{\mathcal{N}_i},\Gamma\_I^{t_{c-1}}_{\mathcal{L}_f},\Gamma\_II^{t_{c-1}}_{\mathcal{L}_f}\right) \\ &= \left[\left(\omega\times\log\left(\frac{\left(\Gamma\_I^{t_{c-1}}_{\mathcal{L}_f} + I^{\mathcal{L}_f}_{\mathcal{N}_i}\right)}{\mathfrak{M}_f} + \xi\right)\right) + \varepsilon\right] \\ &\quad + \left[\tau\times exp\left(\frac{\left(\Gamma\_II^{t_{c-1}}_{\mathcal{L}_f} + II^{\mathcal{L}_f}_{\mathcal{N}_i}\right)}{\mathfrak{M}_f}\right) + \psi\right] \\ &\begin{cases} I^{\mathcal{L}_f}_{\mathcal{N}_i} = \left(\chi^{\mathcal{L}_f}_{\mathcal{N}_i}\times\Upsilon^{t_c}_{\mathcal{N}_i}\right) \text{and } II^{t_c}_{\mathcal{L}_f} = 0, & \text{if } \Upsilon^{t_c}_{\mathcal{N}_i} \text{is classI} \\ II^{\mathcal{L}_f}_{\mathcal{N}_i} = 0 \text{ and } II^{t_c}_{\mathcal{L}_f} = \left(\chi^{\mathcal{L}_f}_{\mathcal{N}_i}\times\Upsilon^{t_c}_{\mathcal{N}_i}\right), & \text{otherwise} \end{cases} \end{aligned} \tag{11}$$

where $\chi^{\mathcal{L}_f}_{\mathcal{N}_i}$ is the ratio of $\Upsilon^{t_c}_{\mathcal{N}_i}$'s division for the $\mathcal{L}_f$ where $0 \leq \chi^{\mathcal{L}_f}_{\mathcal{N}_i} \leq 1$. $\Gamma\_I^{t_{c-1}}_{\mathcal{L}_f}$ and $\Gamma\_II^{t_{c-1}}_{\mathcal{L}_f}$ are the total amount of class I and class II data services in the $\mathcal{L}_f$ at time t_{c-1}. ω, ξ, ε are coefficient factors for the class I data service, and τ,

ψ are coefficient factors for the class II data service. For the other bus channel $\mathcal{L}_s$, the $\mathcal{L}_s$'s utility function, i.e., $U_{\mathcal{N}_i}^{\mathcal{L}_s}(\cdot)$, is defined as the same manner as the $U_{\mathcal{N}_i}^{\mathcal{L}_f}(\cdot)$. In the $\mathbb{G}_{\mathcal{N}_i}^{L}$, the $\chi_{\mathcal{N}_i}^{\mathcal{L}_f}$ is dynamically decided for the $\mathcal{N}_i$ according to the *RBEBS*.

$$
\begin{aligned}
&RBEBS_{\left(\chi_{\mathcal{N}_i}^{\mathcal{L}_f}\right)}(\mathfrak{U}, \mathcal{D})\\
&= \underset{0\le\chi_{\mathcal{N}_i}^{\mathcal{L}_f},\chi'^{\mathcal{L}_f}_{\mathcal{N}_i}\le 1}{\mathbf{argmin}} \left[\left|\mathfrak{X}\left(\chi_{\mathcal{N}_i}^{\mathcal{L}_f}\right) - X\left(\chi'^{\mathcal{L}_f}_{\mathcal{N}_i}\right)\right|\right]\\
&\text{s.t.,} \begin{cases}
\mathfrak{U} = \left\{U_{\mathcal{N}_i}^{\mathcal{L}_f}(\cdot), U_{\mathcal{N}_i}^{\mathcal{L}_s}(\cdot)\right\} \text{ and } D = \left\{d_{\mathcal{L}_f}, d_{\mathcal{L}_s}\right\}\\
\mathfrak{X}\left(\chi_{\mathcal{N}_i}^{\mathcal{L}_f}\right) = \dfrac{\mathcal{C}_{\chi_{\mathcal{N}_i}^{\mathcal{L}_f}}\left(U_{\mathcal{N}_i}^{\mathcal{L}_f}\left(\chi_{\mathcal{N}_i}^{\mathcal{L}_f}, \Upsilon_{\mathcal{N}_i}^{t_c}, \Gamma\_I_{\mathcal{L}_f}^{t_c-1}, \Gamma\_II_{\mathcal{L}_f}^{t_c-1}\right)\right)}{\mathcal{C}_{\chi_{\mathcal{N}_i}^{\mathcal{L}_f}}(D)}\\
\mathfrak{X}\left(\chi'^{\mathcal{L}_f}_{\mathcal{N}_i}\right) = \dfrac{\mathcal{C}_{\chi'^{\mathcal{L}_f}_{\mathcal{N}_i}}\left(U_{\mathcal{N}_i}^{\mathcal{L}_f}\left(\chi'^{\mathcal{L}_f}_{\mathcal{N}_i}, \Upsilon_{\mathcal{N}_i}^{t_c}, \Gamma\_I_{\mathcal{L}_f}^{t_c-1}, \Gamma\_II_{\mathcal{L}_f}^{t_c-1}\right)\right)}{\mathcal{C}_{\chi'^{\mathcal{L}_f}_{\mathcal{N}_i}}(D)}
\end{cases}
\end{aligned}
\tag{12}
$$

where $\mathcal{C}_{\chi_{\mathcal{N}_i}^{\mathcal{L}_f}}(\cdot)$ and $\mathcal{C}_{\chi'^{\mathcal{L}_f}_{\mathcal{N}_i}}$ are the cardinality of $\chi_{\mathcal{N}_i}^{\mathcal{L}_f}$ and $\chi'^{\mathcal{L}_f}_{\mathcal{N}_i}$ where $\chi_{\mathcal{N}_i}^{\mathcal{L}_f} \neq \chi'^{\mathcal{L}_f}_{\mathcal{N}_i}$. Based on the equation (3), the $\mathcal{C}(\cdot)$ can be interpreted as a measure of the size of player's concession. The value of $\chi_{\mathcal{N}_i}^{\mathcal{L}_f}$ is multiples of $\Delta\chi_{\mathcal{N}_i}^{\mathcal{L}_f}$, and we set $\Delta\chi_{\mathcal{N}_i}^{\mathcal{L}_f} = 0.1$ for the computation simplicity. If the value of $\chi_{\mathcal{N}_i}^{\mathcal{L}_f}$ is obtained according to (12), the value of $\chi_{\mathcal{N}_i}^{\mathcal{L}_s}$ is spontaneously decided as $\chi_{\mathcal{N}_i}^{\mathcal{L}_s} = \left(1 - \chi_{\mathcal{N}_i}^{\mathcal{L}_f}\right)$.

D. MAIN STEPS OF PROPOSED CAN TRAFFIC CONTROL SCHEME

Intelligent vehicle technology, such as the CAN system, is widely used in automobiles, trucks, and public transportation. In intelligent vehicles, ECUs handle intelligent functions and control different features. During the ECU communications, various data types, including hard and soft real-time data, share the limited CAN network bandwidth even though they have different real-time requirements. Usually, hard real-time class I data become completely useless when their transmission is delayed beyond a certain time limit, while soft real-time class II data can be tolerable after their time delay limits. In this study, we incorporate the role of two-step cooperative game model into our dual-channel CAN traffic control scheme. At the upper level game, we regulate the traffic amount of individual ECUs while implementing the concept of *MREBS*. It can effectively avoid the CAN traffic congestion situation. At the lower level game, each ECU distributes its data into two bus channels by using the idea of *RBEBS*. It enables the traffic balance between two channels for CAN communications. Based on our two-step cooperative game approach, we can get a fair-efficient solution while sustaining many advantages under widely different and diversified CAN traffic situations.

Usually, control algorithms have exponential time complexity in order to solve classical optimal problems. These methods are impractical to be implemented for realistic system operations. In this study, we do not focus on trying to get an optimal solution based on the traditional optimal approach. But instead, the decision mechanism in our two-step game model is implemented with polynomial complexity. Therefore, it is suitable approach for the real world CAN system in the point view of practical operations. The main steps of the proposed scheme can be described as follows:

- **Step 1:** For our simulation model, the values of system parameters and control factors can be discovered in Table 2 , and the simulation scenario is given in Section IV.
- **Step 2:** In each discrete time period in T, individual $\mathcal{N} \in \mathbb{N}$ generate independently their data $\mathcal{Q}_{\mathcal{N}}$ with service type and delay sensitivity features (η and β).
- **Step 3:** If total data requests from $\mathcal{N}$ $\left(\sum_{\mathcal{N}_i\in\mathbb{N}} \mathcal{Q}_{\mathcal{N}_i}\right)$ is less than the $\mathfrak{M}_T$, $\Theta_{\mathcal{N}}$ can be assigned to fully support $\mathcal{Q}_{\mathcal{N}}$. Otherwise, $\Theta_{\mathcal{N}}$ value is decided through the concept of *MREBS*.
- **Step 4:** At the upper-level game, the $\mathcal{N}_i$'s utility function, i.e., $U_{\mathcal{N}_i}^{U}(\cdot)$, is defined by using (9), and the $\Theta_{\mathcal{N}_i}$ value is formally derived from the equation (10).
- **Step 5:** According to the $\Theta_{\mathcal{N}_i}$ value, the traffic amount $\Upsilon_{\mathcal{N}_i}$ is allocated to the $\mathcal{N}_i$; it can be transmitted by using $\mathcal{L}_f$ and $\mathcal{L}_s$ channels.
- **Step 6:** At the lower-level game, each $\mathcal{N}_{1\le i\le n}$ distributes its $\Upsilon_{\mathcal{N}_i}$ into $\mathcal{L}_f$ and $\mathcal{L}_s$ channels based on the concept of *RBEBS*.
- **Step 7:** In the viewpoint of $\mathcal{N}_i$, the $\mathcal{L}_f$'s utility function, i.e., $U_{\mathcal{N}_i}^{\mathcal{L}_f}(\cdot)$, is defined according to (11). The $\mathcal{L}_s$'s utility function, i.e., $U_{\mathcal{N}_i}^{\mathcal{L}_s}(\cdot)$, is defined as the same manner as the $U_{\mathcal{N}_i}^{\mathcal{L}_f}(\cdot)$.

$$
U_{\mathcal{N}_i}^{U}\left(\mathcal{Q}_{\mathcal{N}_i}^{t_c}, \Theta_{\mathcal{N}_i}^{t_c}, \eta, \beta\right) = \begin{cases}
\gamma - exp\left(-\eta \times \dfrac{\min\left(\mathcal{Q}_{\mathcal{N}_i}^{t_c}, \Theta_{\mathcal{N}_i}^{t_c}\right)}{\Theta_{\mathcal{N}_i}^{t_c}}\right), & \text{if} \mathcal{Q}_{\mathcal{N}_i}^{t_c} \text{is class I}\\
\dfrac{\sigma}{\alpha + exp\left(-\beta \times \dfrac{\min\left(\mathcal{Q}_{\mathcal{N}_i}^{t_c}, \Theta_{\mathcal{N}_i}^{t_c}\right)}{\Theta_{\mathcal{N}_i}^{t_c}}\right)}, & \text{if } \mathcal{Q}_{\mathcal{N}_i}^{t_c} \text{is class II}
\end{cases}
\tag{9}
$$

TABLE 2. System parameters used in the simulation experiments.

Parameter	Value	Description
n	10	the total number of ECUs
$\mathfrak{M}_f$, $\mathfrak{M}_s$	1.2, 0.8 Gbps	bandwidth amounts for the $\mathcal{L}_f$ and $\mathcal{L}_s$
$\mathcal{B}_u$	512 Kbps	basic bandwidth unit for bandwidth allocation
γ	1.5	coefficient factor for class I data services in $U_{\mathcal{N}}^{\mathcal{U}}(\cdot)$
η	{0.5, 1, 1.5}	an adjustment parameter for class I data services in $U_{\mathcal{N}}^{\mathcal{U}}(\cdot)$
σ, α	1, 1	coefficient factors for class II data services
β	{1, 2, 4}	an adjustment parameter for class II data services
ω, ξ, ε	-3, 1, 1	coefficient factors for class I data services in $U_{\mathcal{N}}^{\mathcal{L}}(\cdot)$
τ , ψ	-0.3, 1.3	coefficient factors for class II data services in $U_{\mathcal{N}}^{\mathcal{L}}(\cdot)$
n	10	the total number of ECUs

Traffic Type	Application	Bandwidth Requirement	Priority	Service duration
I	1	3 Mbps (hard limit)	$\eta = 0.5$	60 t
	2	6 Mbps (hard limit)	$\eta = 1$	100 t
	3	9 Mbps (hard limit)	$\eta = 4$	80 t
II	4	4 Mbps (soft limit)	$\beta = 1$	120 t
	5	8 Mbps (soft limit)	$\beta = 2$	90 t
	6	12 Mbps (soft limit)	$\beta = 4$	150 t

Step 8: In the dual-channel CAN system platform, multiple ECUs collaborate with each other in a coordinated manner. Therefore, the proposed approach can strike the appropriate performance balance while adaptively ensuring the efficiency and fairness.

Step 9: Constantly, individual ECUs are self-monitoring the current CAN traffic conditions, and proceed to Step 2 for the next two-step cooperative game process.

IV. PERFORMANCE EVALUATION

In this section, we use computer simulations to study the properties of our CAN traffic control method, and discuss the difference between our scheme and the existing protocols such as the *QMMC*, *RTBA* and *DCCC* schemes shown in [4]-[6]. To develop our simulation model, we have used the simulation language 'MATLAB' to evaluate the proposed scheme and compare it to other schemes. MATLAB is widely used in academic and research institutions as well as industrial enterprises. To validate our approach, we show the advantages and performance improvements of our algorithm on the dual-channel CAN system platform. First, we describe the experimental settings and simulation scenario, and then, present the numerical analysis. The assumptions of our simulation environments are as follows:

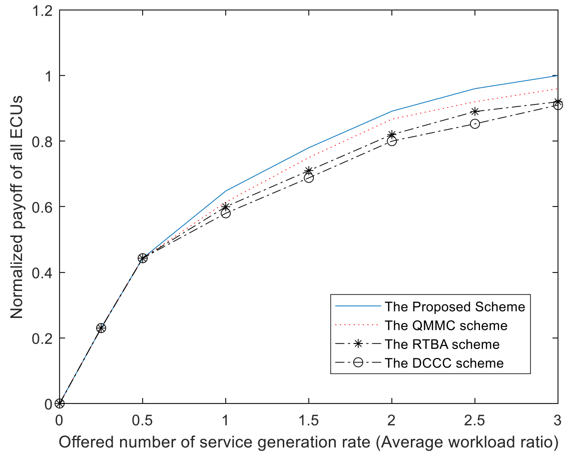

FIGURE 1. Normalized ECU payoff.

- The simulated dual-channel CAN system platform consists of 10 ECUs where $|\mathbb{N}| = 10$.
- Multiple ECUs are locally dispersed over the vehicle structure; they are connected into the $\mathcal{L}_f$ and $\mathcal{L}_s$ to share the bus bandwidth ($\mathfrak{M}_T$).
- Each ECU generate its data for the CAN service. The generation process for data services is Poisson with rate Λ (services/t), and the range of offered services was varied from 0 to 3.0.
- The bandwidth capacities of $\mathcal{L}_f$ and $\mathcal{L}_s$ are 1.2 Gbps and 0.8 Gbps, respectively. Therefore, $\mathfrak{M}_T = \mathfrak{M}_f + \mathfrak{M}_s =$ 2 Gbps.
- Six different kinds of data services are assumed based on their bandwidth requirements ($\mathcal{Q}_{\mathcal{N}}$), priorities for the delay sensitivity (η, β), and service duration times; they are assumed as the CAN's traffic load.
- To reduce computation complexity, the amount of bandwidth allocation is specified in terms of basic bandwidth unit ($\mathcal{B}_u$), where one $\mathcal{B}_u$ is the minimum amount (e.g., 512 Kbps in our system) of computation process. The value of $\chi_{\mathcal{N}}^{\mathcal{L}}$ is multiples of $\Delta\chi_{\mathcal{N}}^{\mathcal{L}} = 0.1$ where $0 \le \chi_{\mathcal{N}}^{\mathcal{L}} \le 1$.
- System performance measures obtained on the basis of 100 simulation runs are plotted as a function of the offered service request load.
- Performance measures obtained are normalized ECU payoff, CAN system throughput and bandwidth utilization in the dual-channel CAN infrastructure

Fig.1 shows the normalized payoff of all ECUs as a function of the service generation rate increase. It is worth reiterating that one of our proposed scheme's benefits is an ability to respond to current CAN traffic conditions while adaptively making control decisions to offer an attractive CAN performance. Therefore, we can leverage selfish ECUs to work together for their profits. This cooperative control paradigm is realized by employing the *MREBS* and *RBEBS*, and it can lead to a higher ECU's payoff than other existing *QMMC*, *RTBA* and *DCCC* schemes under heavy CAN traffic load intensities.

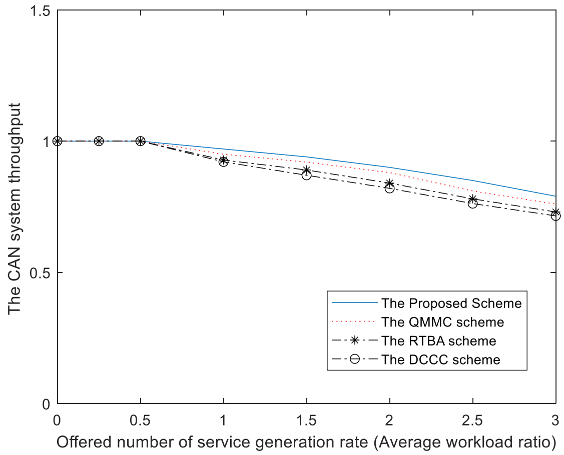

FIGURE 2. The CAN system throughput.

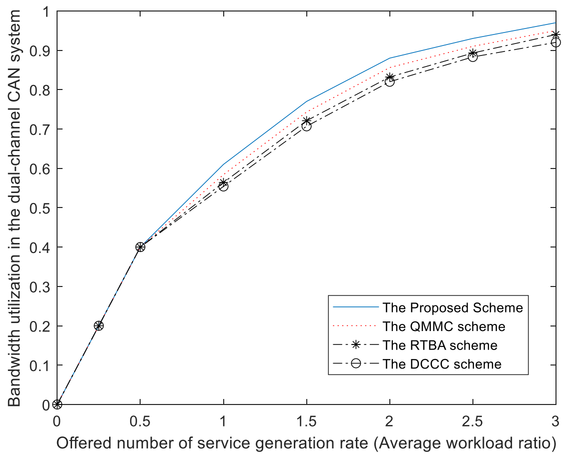

FIGURE 3. Channel bandwidth utilization.

In order to effectively operate the complex and complicated dual-channel CAN infrastructure, the system throughput is a very important performance criterion. In this study, CAN system throughput is the ratio of data services that are completed successfully to all requested data services. Therefore, no throughput gain is accrued for class I data services that fail to meet their delay deadlines. Usually, the major challenge to develop new cooperative game solutions is to provide the most proper combination of the efficiency and fairness. Our two-phase cooperative game approach can effectively compromise the different data services while ensuring the most proper resource sharing. So we can attain the better CAN system throughput than other existing state-of-the-art protocols.

Fig.3 provides the bandwidth utilization of dual-channel CAN platform. Since the bandwidth utilization is strongly related to the ECUs' data communications, the simulation results are similar to those in Fig.1. As expected, we observe that when the service generation rate is low ($\Lambda \leq 1$), the performance of the all schemes is identical. This is because all schemes have enough bandwidth to accept the requested data services. Therefore, all schemes make no difference in the ECU payoff, throughput and bandwidth utilization. However, as the service generation rate increases, the available CAN resource decreases. The major observation here is that our two-phase cooperative game approach can efficiently share the limited system bandwidth resource to operate CAN services. From the simulation results in Fig.1-Fig.3, it is evident that our proposed scheme can maintain the better system performance than other existing *QMMC*, *RTBA* and *DCCC* schemes under diversified CAN traffic condition changes.

V. SUMMARY AND CONCLUSIONS

Since it was introduced about 30 years ago, the CAN has steadily gained popularity and has been adopted in a variety of embedded, networked control systems. One peculiar facet of the CAN protocol is its bus-line mechanism, which is an efficient way to ensure the vehicle communication system. In this study, we investigate the CAN traffic control problem, and develop a new two-phase cooperative game model by using the concepts of *MREBS* and *RBEBS*. At the first phase, the traffic amount for each ECU is adaptively decided according to the *MREBS*. At the second phase, each individual ECU may balance fair-efficiently its service data between two channels based on the *RBEBS*. During the step-by-step operation, our two-phase cooperative game process attempts to provide iteratively different data services in order to optimize the usage of the CAN system resource. Finally, we test our method by using extensive simulation experiments, and confirm the effectiveness of our protocol. As a result, we conclude that our proposed scheme is a feasible and effective approach that can realistically be applied into the dual-channel CAN system as compared with the existing *QMMC*, *RTBA* and *DCCC* schemes.

Research on the dual-channel CAN traffic control problem is still in its infancy. An interesting continuation of our study presented in the paper can be extended in a number of ways. One future direction is to design a new tracking controller by considering the CAN-bus-induced delays. Another potential direction for the future research is to investigate a new methodology, which can manage efficiently the trade-off concerning accuracy, speed, and convergence issues. In addition, we will develop the CAN security functionalities, such as encryption or message authentication.

COMPETING OF INTERESTS

The author declares that there are no competing interests regarding the publication of this paper.

AUTHOR' CONTRIBUTION

The author is a sole author of this work and ES (i.e., participated in the design of the study and performed the statistical analysis).

AVAILABILITY OF DATA AND MATERIAL

Please contact the corresponding author at *swkim01@sogang.ac.kr*.

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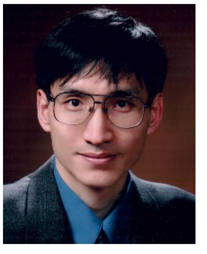

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