

Agent-Based Simulation and Analysis of Network-Centric Air Defense Missile Systems

Su-Yan Tang, Wei Zhang, Shan Mei and Yi-Fan Zhu

Abstract—Network-Centric Air Defense Missile Systems (NCADMS) represents the superior development of the air defense missile systems and has been regarded as one of the major research issues in military domain at present. Due to lack of knowledge and experience on NCADMS, modeling and simulation becomes an effective approach to perform operational analysis, compared with those equation based ones. However, the complex dynamic interactions among entities and flexible architectures of NCADMS put forward new requirements and challenges to the simulation framework and models. ABS (Agent-Based Simulations) explicitly addresses modeling behaviors of heterogeneous individuals. Agents have capability to sense and understand things, make decisions, and act on the environment. They can also cooperate with others dynamically to perform the tasks assigned to them. ABS proves an effective approach to explore the new operational characteristics emerging in NCADMS. In this paper, based on the analysis of network-centric architecture and new cooperative engagement strategies for NCADMS, an agent-based simulation framework by expanding the simulation framework in the so-called System Effectiveness Analysis Simulation (SEAS) was designed. The simulation framework specifies components, relationships and interactions between them, the structure and behavior rules of an agent in NCADMS. Based on scenario simulations, information and decision superiority and operational advantages in NCADMS were analyzed; meanwhile some suggestions were provided for its future development.

Keywords—air defense missile systems, network-centric, agent-based simulation, simulation framework, information superiority, decision superiority, operational advantages

I. INTRODUCTION

NETWORK-Centric Air Defense Missile Systems (NCADMS), as a new network-centric combat system of systems (SoS), is one of the major research issues in military domain at present.

One NCADMS is composed of several kinds of sensors, shooters and C2 nodes connected in a distributed network[1]. Its architecture can adapt dynamically to current operational situation, due to the nonexistence of fixed units (each unit includes a C2 node, a sensor and a shooter for missiles launches)[2, 3]. In order to overcome individual unit limita-

tions, each C2 node has authority with controlling shooters and sensors which are non-located.

Modeling and simulation (M&S) is an effectively supportive approach to the operational analysis of NCADMS. Compared with equation-based approaches such as the Lanchester equations, M&S has the advantage of obtaining knowledge of the operational capabilities in NCADMS, because NCADMS is a new complex nonlinear combat SoS[4] and we know little about it.

The networked operational characteristics and flexible architectures of NCADMS put forward new requirements and challenges for simulations, not only in simulation frameworks in which the complex dynamic interactions among entities need to be mimicked; but also in models that should be composable during the countermeasure simulation process in order to describe the flexible structures of NCADMS.

It is believed that Agent-Based Simulation (ABS) is an appropriate approach to NCADMS simulations. ABS differs from traditional kinds of constructive simulations in that it explicitly attempts to model specific behaviors of specific individuals. It has been examined as an appropriate approach to represent NCW in a combat simulation. The reasons why we choose ABS lie in: (1) we know the behaviors of entities in NCADMS and interactions among them, even though we have not accumulated overall knowledge of that; (2) agents have abilities of awareness and reasoning, which can present the operational characteristics of NCADMS in information and cognitive domain; (3) each agent, representing an entity, performs tasks independently and interact with others flexibly and dynamically in NCADMS. The simulation models of NCADMS can be composable during the course of simulations by using the techniques of ABS; (4) agents are active, which can describe the synchronization of entities in NCADMS; (5) we can explore the optimal cooperation rules among C2 nodes in NCADMS by setting the behavior rules and analyzing the consequent performance of the whole systems.

Large countermeasure agent-based simulation systems have been developed to explore new war-fighting capabilities of complex combat SoS, such as EINSTEIN, MANA, WISDOM, SEAS (System Effectiveness Analysis Simulation), etc. SEAS offers a powerful agent-based modeling and simulation environment, which is suitable for exploring network-centric warfare and transformational war-fighting concepts[5-7]. However, it is hard with SEAS to describe the complex cooperative

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capabilities, so that users need program the specific behaviors of entities in SoS themselves.

In this paper, there are two issues under consideration. One is how to develop an agent-based simulation framework for NCADMS. The other is what kind of knowledge can be obtained through analyzing simulation results. In section 2, differences between Platform-centric Air Defense Missile Systems (PCADMS) and NCADMS are compared, and some new cooperative engagement strategies in NCADMS are introduced. In Section 3, an agent-based simulation framework for NCADMS is designed by adding cooperation capabilities of entities, setting the behavior rules of agents and defining the interactions among them based on the new operational characteristics of NCADMS. In Section 4, the information superiority, decision superiority, and the operational advantages of NCADMS are analyzed in a specific scenario. Lastly, we conclude the work.

II. SYSTEM ANALYSIS

One PCADMS is a hierarchy SoS, where sensing and engagement capabilities reside on the same air defense missile unit (unit for short), and there is only limited capability for a unit to engage a target based on awareness generated by other units. A PCADMS and a NCADMS is shown in Fig. 1.

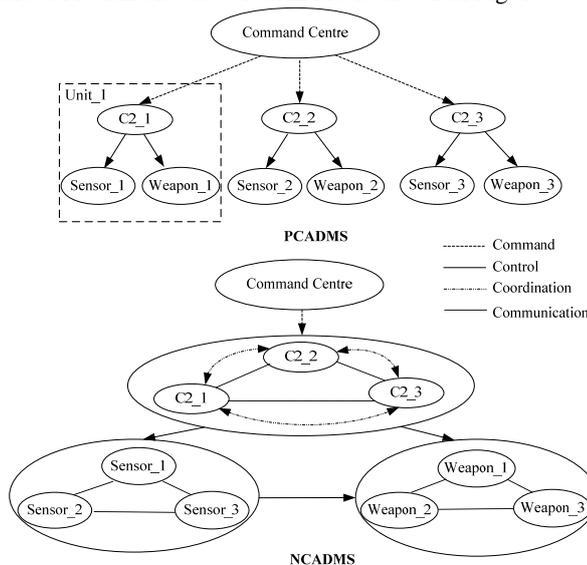


Fig. 1 PCADMS vs. NCADMS

Units in NCADMS are temporarily formed. Based on the current situation, components of units are able to detach themselves from current units and join a newly formed one, in order to overcome individual limitations. Units can also achieve shared battle-space awareness through enhanced networks and common processing. Each C2 node in a specific unit has authority with selecting the best shooter and lift constraint of organic sensor/weapon pairing for engagements.

C2 nodes in NCADMS enable to communicate, negotiate and coordinate with each other under the same operational intent from superior commanders. In order to overcome individual unit limitation, each C2 node also has authority with

controlling shooters and sensors which are non-collocated.

Warfare assets¹ in NCADMS can form new important cooperative engagement strategies[8, 9], including *Precision Cue*, *Launch on Remote*, *Engage on Remote*, *Forward Pass*, and *Remote Fire* as shown in TABLE I.

TABLE I
NEW COOPERATIVE ENGAGEMENT STRATEGIES IN NCADMS

Name	Definition
Precision Cue	A cue of a specific target received from a remote unit can be used to direct a local sensor to detect the target. The cue is comprised of target information such as a state estimate, target track data, and/or an assessment of the target's identification.
Launch on Remote	Remote sensor data about a specific target can be used by a local unit to initiate a missile launch without holding the track locally.
Engage on Remote	A firing unit can make the launch decision by using the remote data, and remote unit also support the entire engagement, such as in-flight guidance and illumination of missiles.
Forward Pass	The control of in-flight missile can be forward passed to another unit to complete the intercept.
Remote Fire	A remote unit transfers the launch decision to a local unit, which will initiate a missile launch for the remote unit to intercept a specific target. Engagement control can be performed by the remote unit or can be passed to the firing unit.

III. AGENT-BASED SIMULATION FRAMEWORK

A. Components

Mimicking the components in SEAS, there are three primary components in NCADMS simulation system: agent, device and environment.

(1) An agent is an operational entity which has capability to make decision, sense and understand things, talk to other agents, utilize and acquire resources, and kill other agents in a combat environment, such as air defense missile units and command centre in NCADMS; ships, units and planes in attack side, etc.

(2) A device does not have capability to make decision. It is controlled by an agent to interact with others and the environment. Typical devices in NCADMS are air defense missiles, satellites, sensors, communications, etc.

(3) Environment is the battle-space, such as location, terrain, weather, jamming and day/night characteristics, etc. It affects the behaviors of agents and performance of devices.

B. Relationships between Components

(1) Agent and Device

A device belongs to an agent. It can be used to detect or fire upon enemy entities, and communicate with other agents in the same side. For example, sensors, air defense missiles and communications belong to a unit of NCADMS.

(2) Agent and Agent

An agent obtains orders from a superior one (e.g. command centre). Target information detected by an agent will be shared in the same side.

¹ Warfare assets in NCADSM are sensors, weapons, command and control systems, warfare units and platforms.

According to the intent of superior commanders, agents of the same side can detect the enemy warfare assets by sensors, or fire upon them individually or cooperatively by weapons. Agents in NCADMS can also perform the new engagement strategies cooperatively.

(3) Agent and Environment

Environment mainly affects sensor range and probability of detection, weapons range and probability of kill, and communications range and reliability. Actions of agents will be adapted consequently.

C. Interactions

Based on the new cooperative engagement strategies, we design the interactions between agents in NCADMS as shown in Table II. Table III describes the interactions between agents and environment.

TABLE II
INTERACTIONS BETWEEN AGENTS OF NADMS

Name	Definition
TargetSightSig	Target sightings shared among agents, to perform strategies of Precision Cue and Launch on Remote.
BVSig	Broadcast information among agents.
CommandSignal	Orders from superiors
CoEngageReqSig	Coordination messages about Engage on Remote (while guidance radar hasn't traced target) and Remote Fire (while guidance radar has traced target).
GuidanceReqSig	Coordination messages about Forward Pass
GuidanceProvSig	Information about Forward Pass that an agent provide to another one.
InterceptResultSig	Conflict outcomes about a specific target

TABLE III
INTERACTIONS BETWEEN AGENTS AND ENVIRONMENT

Name	Definition
ITerrain	Public interface of agents getting terrain information
IWeather	Public interface of agents getting weather information

D. Unit Structure

Units are the main operational power in NCADMS. According to the behaviors of units, we expand the agent structure in SEAS by adding a Local Cooperation List (LCL). LCL store messages about the new cooperative engagement strategies. Structure of a unit is shown in Fig. 2.

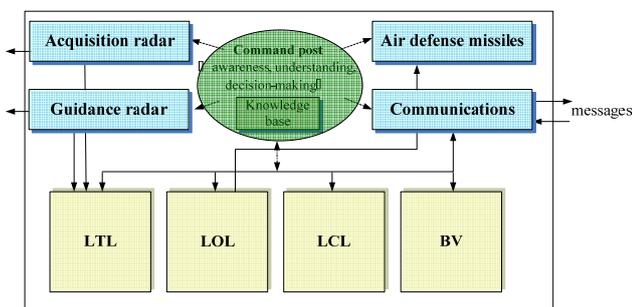


Fig. 2 Structure of a unit in NCADMS

In Fig. 2, knowledge base is composed of operational rules and experience of the commanders. We explicate the structure as following.

(1) Information acquirement

There are four types of messages transmitted in communications - target sightings, orders and command messages, cooperation messages and broadcast variables. A unit obtains target sightings by sensors, or by communications, which receives the target sightings from other units. Shared target information includes location estimate, target track data, and an assessment of the target's identification. Orders and command messages represent the operational intents of superiors. Cooperation messages are used to perform the cooperative engagement strategies. Broadcast variables for a unit include target list, performance parameters of air defense missiles and sensors, location, the number of target passages and missiles, reaction time and intercept results, etc.

(2) Information storage and transmission

LTL (Local Target List), LOL (Local Order List), LCL (Local Cooperation List), and BV (Broadcast Variables) are used to store the different types of messages.

Target Sightings are stored in LTL. As long as LTL gets target detective information, the command post will control the communications to broadcast them in a broadcast interval. LOL stores superior orders and local orders. The behaviors of a unit depend on the superior orders. A local order, which produced by the command post, is used to control the actions of devices. It is prior to a superior one. LCL stores cooperation messages. The command post transforms these messages into local orders to perform the cooperative engagement strategies. BV stores broadcast variables from other units (indexed by unit name). Any one of broadcast variables will be broadcasted in an interval while it changes, and other units will update their BV in time.

(3) Decision-making

Based on the messages, a command post will transmit the superior commander's intents into local orders, make launch decisions, initiate missiles launch for other units, control the devices, and produce the cooperation messages when it needs to perform the new cooperative engagement strategies.

(4) Action

Air defense missile is the final executor for a unit. By the end of the initiative course of a missile, collocated or non-collocated guidance radars will provide mid-course guidance based on the local or shared target information. After exploding the missile, conflict results will be put in LTL and BV. They are always prior to be accessed.

E. Behavior Rules

Units in NCADMS have a set of default behavior rules. Command posts make all kinds of decisions based on these rules. The default behavior rules are:

(1) Usages of shared information

Based on shared information about the specific targets, a unit can direct collocated sensors to detect them. It can also initiate air defense missiles launch to intercept them without holding the track locally.

(2) Requirements to perform *Remote Fire*

Based on the target information, command post of a unit will initiate an air defense missile if the launch decision is

possible. Otherwise, it will make a possible launch decision of another property unit (firing unit) based on the messages in BV to perform the *Remote Fire*. Launch decision (messages passed through “*CoEngageReqSig*”) will be transferred to the firing unit by communications.

(3) Supply to perform *Remote Fire*

After getting the cooperation messages (launch decision) from the interface “*CoEngageReqSig*”, command post of the firing unit checks the current situation and capabilities of itself (such as number of missiles and target passages). If it is capable of supporting the “*Remote Fire*” strategy for another unit, local orders about initiating a missile will be produced based on the launch decisions received.

(4) Requirement to perform *Forward Pass*

Local sensors may not track a target stably because of the limitation of effective range, azimuth angle, jamming, maneuverability of the target, etc, even though the target has been in the effective range of the local air defense missiles. Units in NCADMS have authority with selecting non-collocated guidance radars to perform the engagement control (such as in-flight guidance and illumination) for a collocated missile. It can send a cooperation message through interface “*GuidanceReqSig*” to the unit, whom the guidance radar collocates currently. Additionally, when the air defense missile ADM_i of $Unit_i$ is in the middle course, $Unit_i$ can also send a cooperation message through the interface “*GuidanceReqSig*” to other units, whose guidance radars are capable of improving the guidance precision for ADM_i .

(5) Supply to perform *Forward Pass*

$Unit_j$ checks the current situation and capabilities of itself (such as number of guidance passages, effective range of guidance radars, etc), when it receives the cooperation messages from interface “*GuidanceReqSig*”. If $Unit_j$ enables to perform the engagement control for ADM_i , it will send the cooperation message through interface “*GuidanceProvSig*” to $Unit_i$ and offer the relay guidance.

IV. SIMULATION AND ANALYSIS

Two simulation systems on NCADMS and PCADMS are developed by using the Simulation Model Portability Standards 2 (SMP2) of ESA[10, 11]. Based on the data obtained from scenario Monte Carlo simulations, the information superiority, decision superiority and operational advantages of NCADMS are analyzed, compared with PCADMS.

A. Scenario

Countermine warfare includes two sides, an attack side and a defense side.

In this scenario, the attack side is composed of 10 attack missiles which initiated at intervals of 10 seconds and named after the initiating time. For example, a missile which is initiated firstly called Target1, and the last one called Target10.

The defense side is an ADMS (NCADMS or PCADMS), which includes 5 air defense units (Unit1 to Unit5, each unit includes an acquisition radar, a guidance radar, air defense

missiles, a command post), a command centre, a long-distance warning radar and a warning satellite. One guidance radar is able to track 6 targets and control 12 air defense missiles simultaneously at most. Effective range of the guidance radar in Unit1 and Unit2 for the targets is 400km, others are 120km. The maximum range of the air defense missiles in units is 80km, and the minimum one is 2km. The maximum height is 25km, and the minimum one is 0.03km. The kill probability of a single air defense missile for intercepting a single target is 0.7. Reaction time of each unit is 3s. Every unit has 8 air defense missiles ($N=8$) and defenses under a SLS (Shoot-Look-Shoot) engagement policy. According to the threat degree of targets and performance parameters of units, the command centre performs the centralized weapon-target assignment, and the original and optimal result is shown in Table IV.

TABLE IV
WEAPON-TARGET ASSIGNMENT

Units	Targets
Unit1	Target1
Unit2	Target4, Target8, Target10
Unit3	Target2, Target6, Target9
Unit4	Target3, Target5
Unit5	Target7

B. Information Superiority

It is essential for NCADMS to share information because each unit is able to detect targets earlier and take actions more quickly based on the shared target information. Thus, the first tracked time ($T_{FirstTraced}$) and the first intercepted time ($T_{FirstIntercepted}$) for every target in PCADMS and NCADMS are compared as following.

(1) For the first tracked time

Fig.3 shows the comparison result of $T_{FirstTraced}$ in NCADMS and PCADMS.

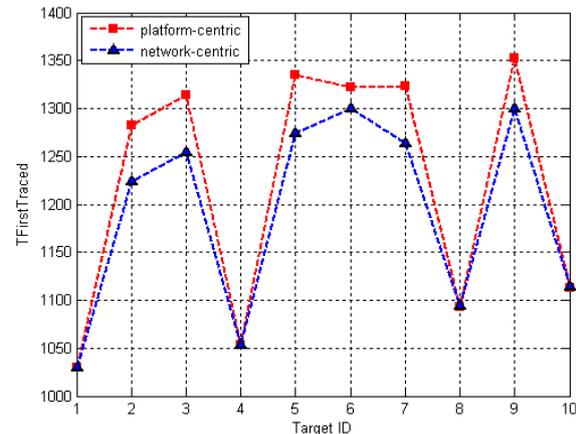


Fig. 3 $T_{FirstTraced}$ s in PCADMS and NCADMS

The effective range of sensors in Unit1 and Unit2 are further. They are providers of shared target information. Therefore, $T_{FirstTraced}$ s of Target1, Target4, Target8 and Target10 in NCADMS and PCADMS are almost the same. However, $T_{FirstTraced}$ s of other targets are earlier in NCADMS because Unit3, Unit4 and Unit5 can perform “*Precision Cue*” based

on the shared target information from Unit1 and Unit2, which have enough passages to track targets assigned to other units.

(2) For the first intercepted time

Fig.4 illustrates the comparison of $T_{FirstIntercepted}$ s for targets in NCADMS and PCADMS.

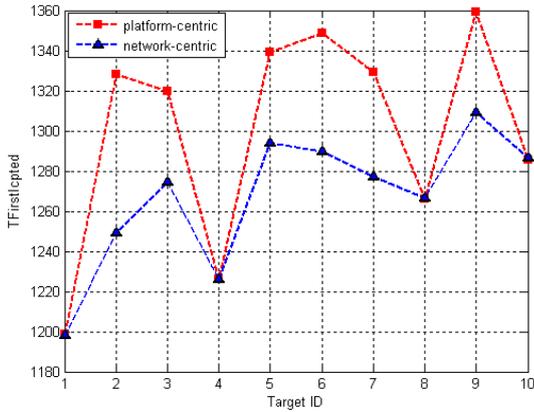


Fig. 4 $T_{FirstIntercepted}$ s in PCADMS and NCADMS

In Fig. 4, $T_{FirstIntercepted}$ s of targets assigned to Unit3, Unit4, and Unit5 are earlier in NCADMS than those in PCADMS. There are two reasons for this phenomenon. One is $T_{FirstTraced}$ s of those targets are earlier benefited from performing the "Precision Cue". Another reason is Unit3, Unit4, and Unit5 can initiate missiles launch without holding the track locally by performing the "Launch on Remote".

C. Decision Superiority

Quality of decisions depends on the available time for decision-making (T_{DM}). The accuracy of decisions will be higher if commanders have enough time to understand and make launch decisions[12]. The T_{DM} ($T_{FirstIntercepted} - T_{FirstTraced}$) of each target in PCADMS and NCADMS are compared as shown in Fig. 5.

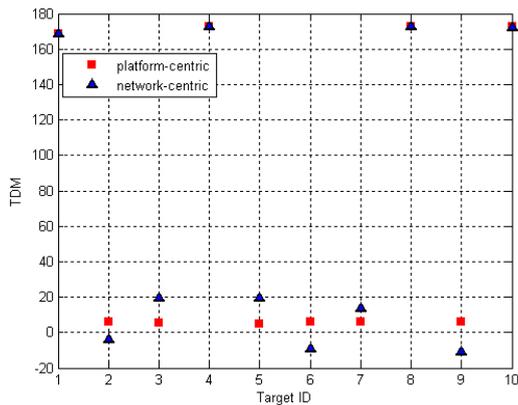


Fig. 5 T_{DM} s in PCADMS and NCADMS

In Fig. 5, T_{DM} s for Target3, Target5 and Target7 are more abundant in NCADMS than those in PCADMS, because $T_{FirstTraced}$ s for the targets above in NCADMS are earlier, com-

manders in NCADMS have enough time for awareness, understanding and decision-making. It also represents that information superiority is transformed into decision superiority in NCADMS.

It is observed that T_{DM} s of Target2, Target6 and Target9 are minus. By collecting the other data in simulations, it is found that Unit3 performs the strategy of "Launch on Remote", and initiates missiles launch earlier without holding the track locally by using the shared target information.

D. Operational Advantages

Two variables are considered as the way that information and decision superiority transformed to operational advantages in NCADMS - E3 range and intercepted times of every target.

(1) E3 Range

Effective Engagement Envelope (E3) is the surrounding region in which a unit can fire air defense missiles at enemy targets [9]. Taking Target6 for example, Fig. 6 illustrates how information superiority of Unit3 transformed into operational advantages. $T_{InRange}$ is the moment that Target6 at the maximum kill range of Unit3.

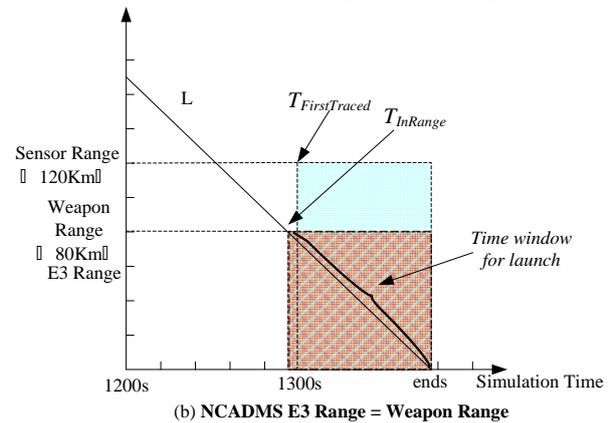
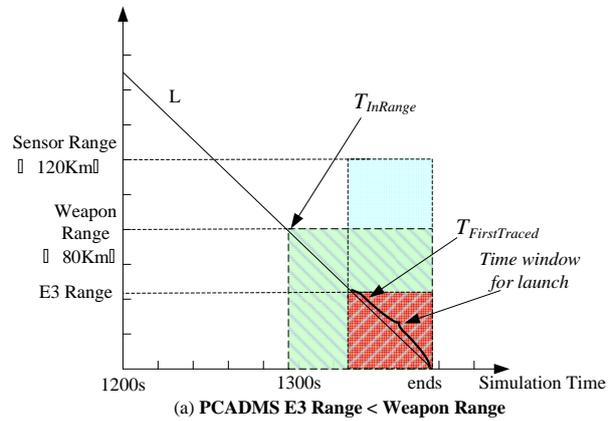


Fig. 6 E3 Range of Unit3 for intercepting Target6

In PCADMS, shown in Fig. 6(a), E3 Range of air defense missiles for a specific target depends on the performance of the collocated guidance radar. A unit can not initiate missiles launch if the collocated guidance radar has not hold the track of a target. Generally speaking, guidance radar and air defense

missiles can not reach their fullest extent, especially for intercepting a low altitude target.

In NCADMS, shown in Fig. 6(b), E3 Range of air defense missiles for a specific target can be expanded, because units have authority with controlling non-allocated guidance radars to perform “Engage on Remote” and “Forward Pass” strategies. Guidance radars are able to hold the track of targets earlier, and E3 Range of a missile for a target will not be restricted by the performance of the collocated guidance radars.

(2) Intercepted Times

Agents can be divided into three groups, which are cooperative agents, selfish agents and hybrid agents, according to the cooperation degree among them. Here, it is assumed that units in NCADMS are cooperative, which means a unit will launch missiles to support “Remote Fire” and “Engage on Remote” strategies for other units, as long as it possesses air defense missiles. Fig. 7 is intercepted times for all targets in PCADMS and NCADMS when N equals to 8.

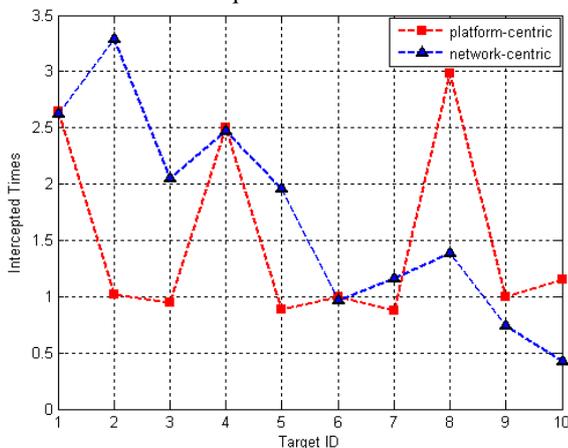


Fig.7 Intercepted times for targets in PCADMS and NCADMS

In Fig. 7, intercepted times of Target2, Target3, Target5 and Target7 are more in NCADMS than those in PCADMS. Information superiority and performance of “Launch on Remote” expand the time windows for missiles launch, and increase the intercepted times of them consequently.

However, intercepted times of Target8, Target9, and Target10 are less in NCADMS than those in PCADMS. By collecting the cooperation times (times of supporting the cooperative engagement strategies for other units) of Unit2 and Unit3, it can be found that their locations are suitable to support “Engage on Remote” and “Remote Fire” strategies for other units. Units in NCADMS are cooperative, and they almost have no missiles to intercept Target8, Target9 and Target10, which arrive later. Although other units can intercept Target8, Target9 and Target10 cooperatively when they passed Unit2 and Unit3, the optimal weapon-target pairings will be changed.

(3) Cooperative vs. Selfish

A selfish unit in NCADMS keeps certain number of missiles to intercept targets assigned to them, whenever they come. For example, Unit2 keeps 2 air defense missiles per target. If a Unit has more missiles left except for the reservations, it will cooperate with others to perform “Engage on

Remote” and “Remote Fire” strategies. Otherwise, it will refuse to initiate missiles launch for others. Fig. 8 illustrates the intercepted times of Target10 when Unit2 is selfish ($S_IcptTimes$) or cooperative ($Co_IcptTimes$).

In Fig. 8, it is observed that (a) $S_IcptTimes > Co_IcptTimes$ if $N \leq 14$; (b) $S_IcptTimes$ is almost equal to $Co_IcptTimes$ and they both increase with N if $14 < N < 20$; (c) if $N > 20$, $S_IcptTimes \approx Co_IcptTimes \approx C$, where C is a constant. Thus it's suggested that a unit in NCADMS can be selfish to keep the optimal weapon-target pairings when the missiles stored are limited; otherwise, the unit should be cooperative to perform those new cooperative engagement strategies well.

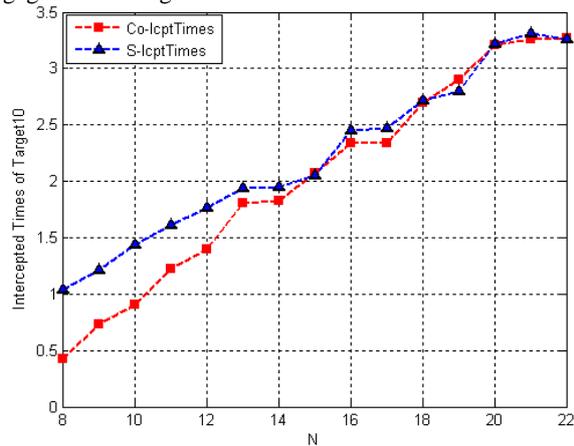


Fig. 8 Intercepted times of Target10

V. CONCLUSION

NCADMS represents the superior development of the ADMS. There are two important problems in NCADMS at present. One is how the network-centric architecture affects its combat effectiveness. The other is how to adapt the traditional operation strategies to improve the whole combat effectiveness of NCADMS. NCADMS is a new combat SoS, ABS is an important approach to solve the problems above. This paper presents an agent-based simulation framework for NCADMS. Based on the scenario simulations, the information superiority, decision superiority and operational advantages of NCADMS are analyzed, and some suggestions of its future development are also provided in this paper. It is well-known that communications reliability, environment, characters and experience of commanders are important factors for a combat SoS. Therefore, the issue on how those factors work on the whole combat effectiveness of NCADMS will be our future work.

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