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Research Article

Agent-Based Simulation and Its Application to Analyze Combat Effectiveness in Network-Centric Warfare Considering Communication Failure Environments

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Many parts of platforms are expected to be replaced by unmanned systems in modern warfare. All the assets and supporting vehicles are linked to each other with a communication network, and it is called the network-centric warfare environment. Hence, it is critical when communication failure occurs during engagement in ground battlefield because this failure will directly affect overall combat effectiveness of one's owned assets. However, research regarding communication failure issues is scarce. We herein propose a new agent-based modeling process to measure the overall combat effectiveness combined with communication success ratio, based on the terrain condition of the ground engagement. Additionally, we provide the effectiveness analysis result when a communication repeater is applied during communication failure as an alternative measure.

1. Introduction

To construct a war-game model, the Lanchester-type equation is a typical tool to generate the value of attrition rates for both sides of the battle. It appears reasonable when the game proceeds unit by unit and asset by asset, which is called the platform-centric warfare. However, it has been rapidly changed, in modern warfare, to the network-centric warfare, in which all platforms are linked to each other to create a large and complex warfare environment.

Therefore, agent-based modeling (ABM) has been used widely to build a war-game model recently, because it can produce more realistic results based on its own decisions and actions for all platforms regarded as agents in a complex system of the battle.

Furthermore, in the previous war-game model, the communication error effect (CEE) was not considered and its possible effect on each weapon system was not reflected either. However, the CEE is an important factor in network-centric warfare because all platforms in a battle are connected to each other to share the target and damage information, as well as exchanging the order and report among related units according to the echelon chain.

The agent-based simulation framework we propose herein consists of three key themes: ABM, CEE, and line of sight (LOS), as shown in Figure 1.

In this study, we consider both ABM and CEEs in a network-centric warfare environment and provide a new modeling process to measure the combat effectiveness in a high resolution war-game model considering communication failure.

As for the quantitative measurement of combat effectiveness (CE), Hayward [1] proposed three factors to quantify CE as capabilities, environment, and missions. However, it is still difficult to measure the quantitative combat effectiveness owing to its intangible and subjective characteristics. It is also

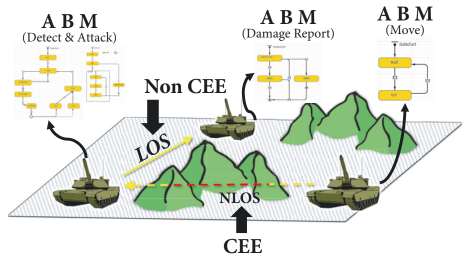

Figure 1: Configuration of a typical battlefield in high resolution.

impractical to measure the CE experimentally. Recently, Kim et al. [2] reported a literature review of the work by CE. Lee and Lee [3] and Lee et al. [4–6] proposed a network-based metric for measuring CE.

ABM related studies in war-game simulation are Hill et al. [7], Cil et al. [8], Seo, et al. [9], Connors et al. [10], and Thomson et al. [11]. Regarding the study of communication factor and modeling in the NCW environment, several researches have reported the partial impact to CE in a particular situation such as Sen et al. [12], Karedal et al. [13, 14], Kang et al. [15], Shin et al. [16], Cheng et al. [17], Li et al. [18], Akhtar et al. [19], Shin et al. [20], and Lee et al. [21].

Our study retains three factors that are different from the papers above because we developed our own model to generate the communication error, provide an alternative measure for communication failure, and compare the CE results with those from the army weapon analysis model (AWAM), which is an official analysis model used in the US and Korean army.

2. Communication Process in NCW

2.1. Overview of Communication Impact to Combat Effectiveness. It is assumed, without loss of generality, that the overall measurement of CE is the probability of success in combat operations. Therefore, the primary measure of effectiveness (MOE) in our model would be the blue survival ratio (BSR), meaning the ratio of remaining assets (when blue wins) over the initial assets for the blue force side against the red force. The study showed how the CEE changes the BSR depending upon the level of communication success probability.

For the representation of CEE, we used terrain map that shows the altitude of the terrain in each specified location. Hence, different altitude levels are expressed by each small cell area depending upon the geographic surface pattern of the battle ground. When the LOS between two platforms is visible, no CEE would be applied. Meanwhile, if the LOS between two platforms is blocked, CEE will occur and the communication success probability (CSP) would be calculated by the model we developed. During the engagement, all orders from command and control (C2) and the responding actions from all platforms such as tanks and unmanned ground vehicles will be delivered via the communication process. The overall structure of the communication process for delivering orders and reports during the engagement is shown in Figure 2.

We also used AnyLogic 7.0 to represent all these processes and conditions to validate the logic in the NCW war-game environment.

2.2. Communication Failure Function. To consider the effect of communication error within a war-game model, we used the path loss model that is a function describing the communication in the physical layer between the transmitter (TX) and receiver (RX) as a method of expressing communication. This model is based on the free path loss function and is implemented by the communication channel environment and the distance between TX and RX. Two types of path loss function used according to the LOS or non-LOS (NLOS) are shown in Table 1.

3. Model Development

3.1. Basic Scenario. To generate the overall measurement of MOE and to estimate the average value of the BSR, a typical scenario was established. The input data are shown in Table 2. A virtual area of size 10 km × 20 km was extracted from the demilitarized zone region and is formulated as a digitized map with each altitude illustrated in each terrain cell. The combat assets were initially deployed to the engagement for both the blue and red sides. The POD and POH for each side were assigned as a linear function depending upon the distance from the firing platform to the target.

3.2. Structure of the Agent-Based Model. The agent-based model proposed consists of three subprograms: primary, unit agent, and subagent. The primary program provides the environment of the battle ground and the generating, positioning, and setting avenues of approach for the unit agent. The unit agent is also known as the platform agent that defines all types of functions that the subagents would perform based on the prespecified rules defined by the unit agent. Subagents are function-oriented agents that perform a mission assigned by the corresponding unit agent.

The overall structure of the agent-based model is shown in Figure 3.

3.3. Process of Communication Agent. Both the TX and RX are always required to perform communication success or failure. Basically, three steps are required to send a message to the receiver such as (1) Comm.On, (2) Sending Msg., and (3) Comm.End. The detailed process is shown in Figure 4.

Table 1: Path loss functions applied to evaluate the communication effect.

Scenario		Path loss [dB]	Shadow fading St[dB]	Applicability range, Ant. Height default value
C1	LOS	(i) A=23.8 B = 41.2, C = 20 (ii) $PL = 40.0\log_{10}(d[m]) + 11.65 - 16.2\log_{10}(h_{rx})$ $-16.2\log_{10}(h_{RX}) + 3.8\log_{10}(f_c\,[GHz]/5.0)$	σ=4 σ=6	30m < d < d_{BP}, d_{BP} < d < 5km, $h_{TX} = 25m, h_{Rx} = 1.5m$
	NLOS	(i) $PL = (44.9 - 6.55\log_{10}(h_{rx}))\log_{10}(d[m]) + 31.46$ $+5.83\log_{10}(h_{rx}) + 23\log_{10}(f_c\,[GHz]/5.0)$	σ=8	50m < d < 5km, $h_{TX} = 25m, h_{Rx} = 1.5m$

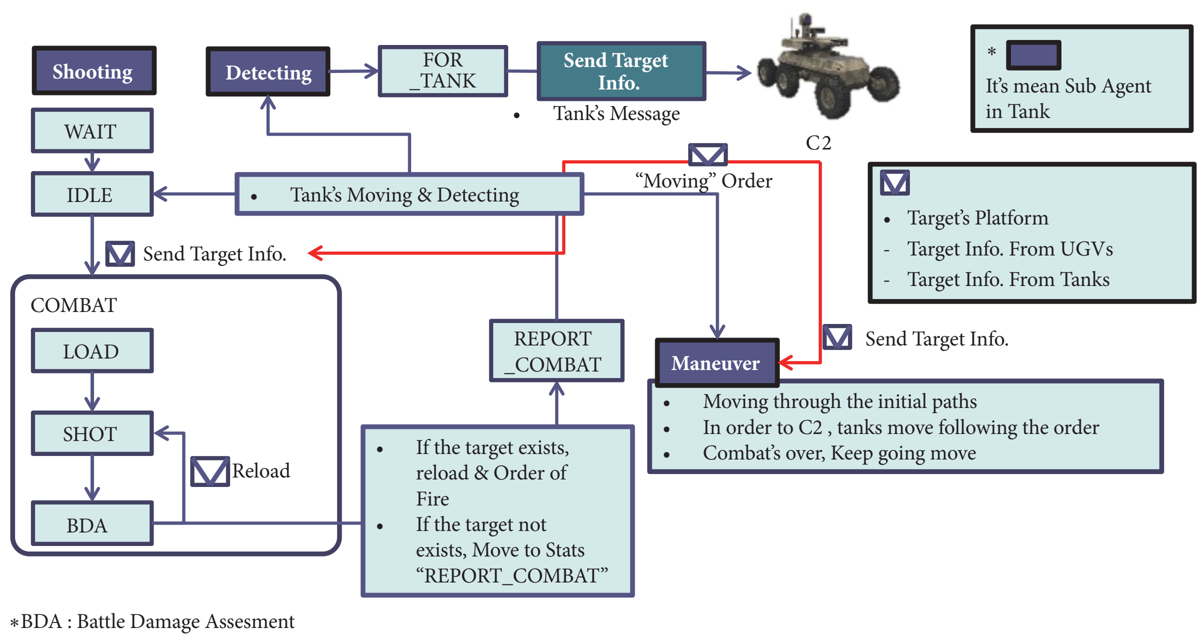

Figure 2: Communication process delivering orders and reports during engagement.

The communication agent serves as an information exchange channel for transmitting and receiving all commandments. For example, a command "fire target" by the detecting agent that can exist in a tank or unmanned ground vehicle (UGV). The overall process of the communication agent is as follows. Both the TX and RX can create a communication agent containing information. Further, the TX sends a message to the RX, known as the "communication start." The Rx that received the message transmits an acknowledgment (ACK) message indicating that the corresponding message has been received from the TX. Subsequently, both channels are open to communication and an information/order such as a specific coordinate or text message can be sent. The success of this process creates the communication agent in the TX, and the RX is deleted after passing the command.

Additionally, if the transmission fails within 2 s, transmission is attempted again. If this process is not successful after three times, we assume that the transmission has failed.

3.4. Process of C2 Agent. The C2 agent delivers all types of messages to either send orders or receive the information required via the communication agent. It assigns orders to the tanks and UGVs. It also collects the enemy target-related

Table 2: A scenario for engagement of ground battle.

Virtual area 20km x 10km 5 reconnaissance routes between blue and red forces		
Terrain Cell		
Cell Size	400 m × 400 m	
the number of Cell	1,250	
Cell's Attribute	Altitude	
Combat Assets		
Blue	Tank	30
	C2	10
	UGV	2
Red	Tank	15
	C2	5
POD (probability of detection) & POH (probability of hit)		
	POD	POH
Blue	$-0.02d[m]+100$	$-0.04d[m]+100$
Red	$-0.013d[m]+100$	$-0.017d[m]+100$

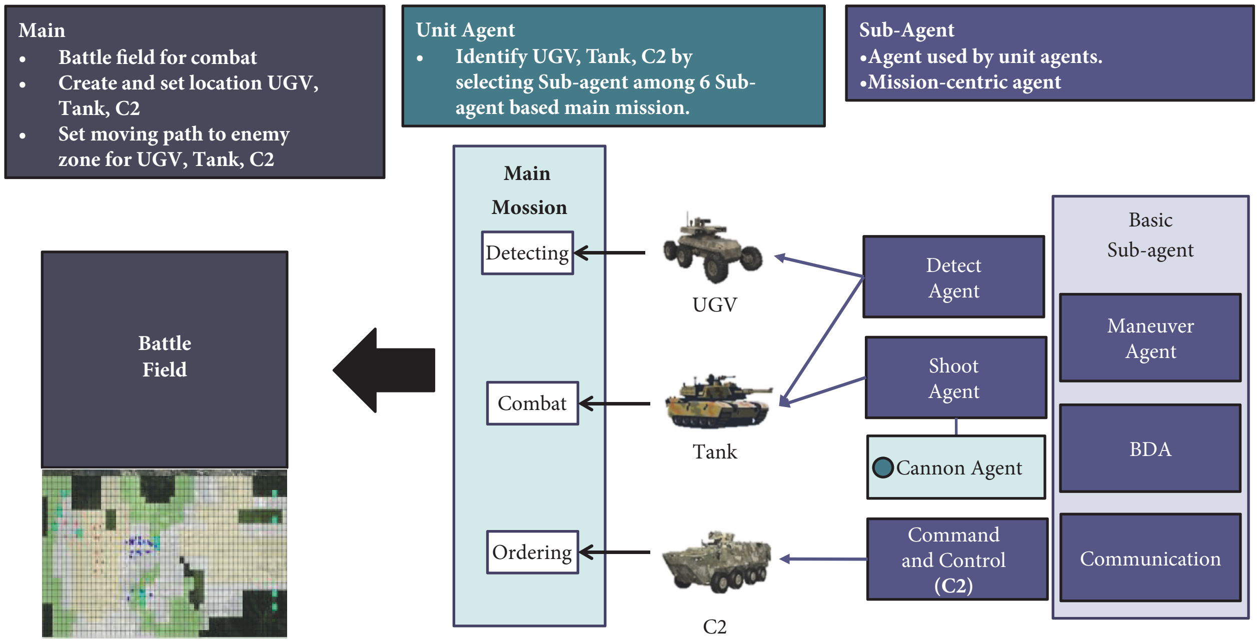

Figure 3: Agent structure of the model.

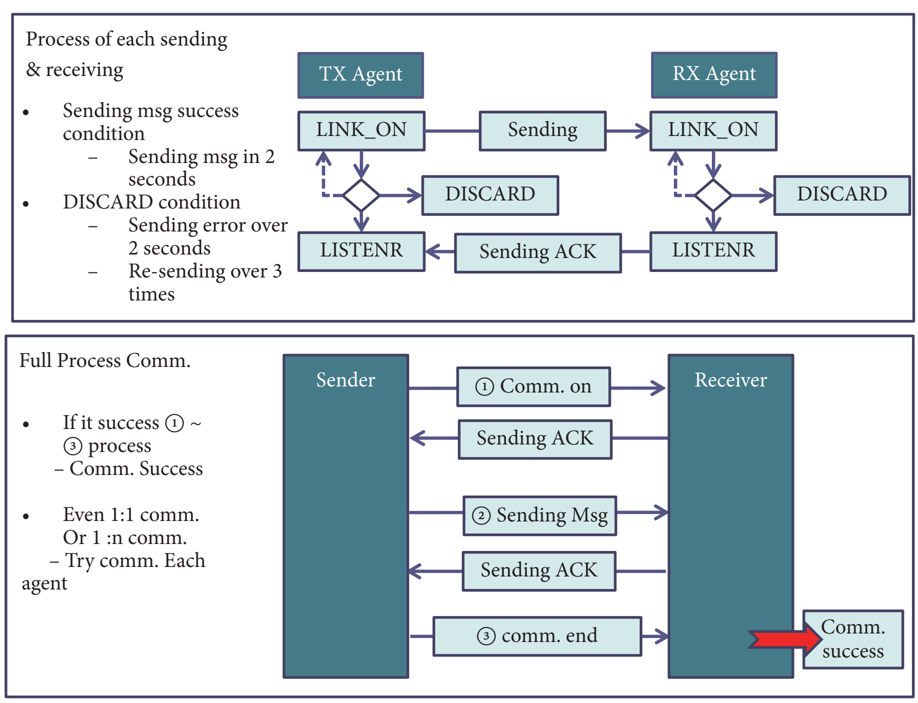

Figure 4: Detailed process of the communication agent.

intelligence. For example, when the UGV finds the enemy target, its information goes to the C2 agent with a message "Find." Subsequently, the C2 agent executes the inner process and assigns an order of either "Move" or "Fire" to the sender. The role and process of the C2 agent is shown in Figure 5.

3.5. Process of BDA Agent. When a battle occurs, we must perform a battle damage analysis (BDA) that produces casualties of both red and blue forces. The BDA agent performs an assessment to calculate the casualties during the battle. When a platform is hit by an adversary weapon, one of three cases occurs: M-Kill, A-Kill, or T-Kill, as follows.

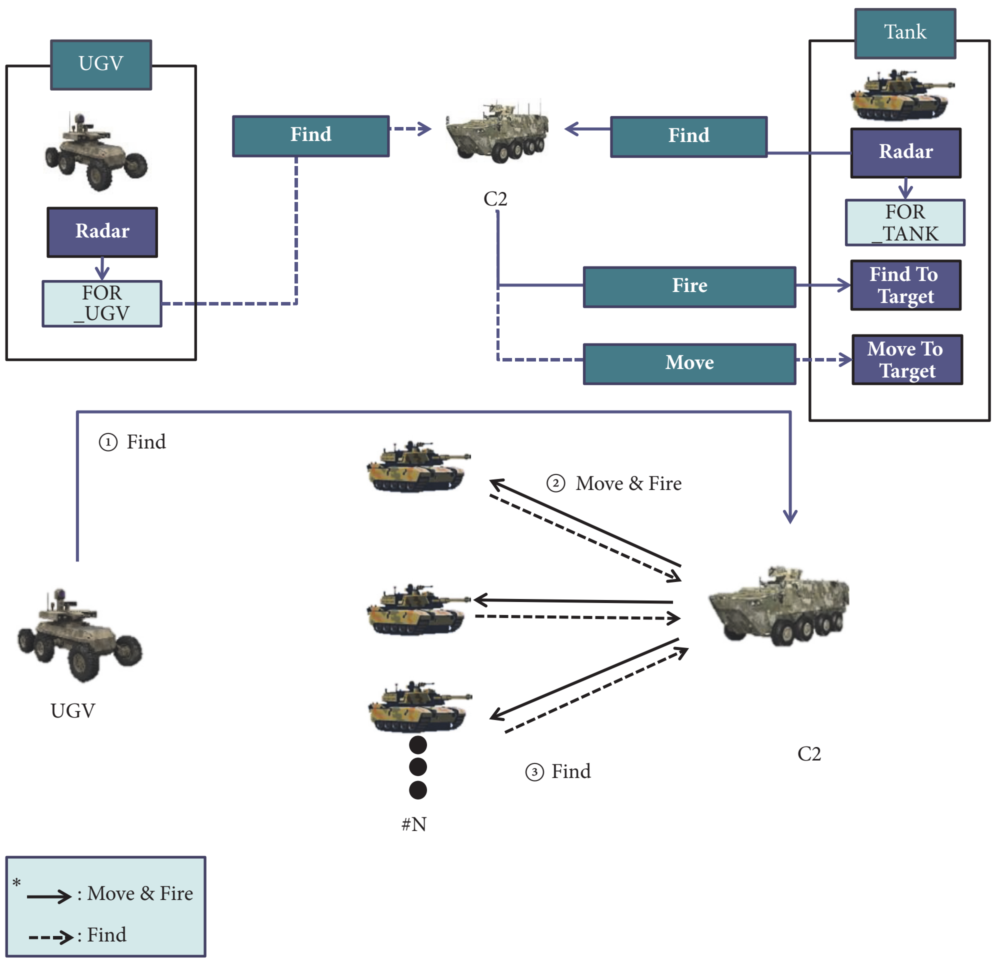

Figure 5: Role and process of C2 Agent.

(1) M-Kill: mobility kill; it cannot move but fires the enemy targets.

(2) F-Kill: fire kill; it cannot fire to aim the targets but moves to other locations.

(3) T-Kill: total kill; it is the case of total destruction in both mobility and firing capability.

Hence, in M-Kill, it remains in position and performs firing whenever required. The maneuvering agent is automatically disconnected by the M-Kill agent.

Meanwhile, in F-Kill, the shooting agent is disconnected and continues moving based on the mission.

When T-Kill occurs, it disappears in the battlefield until the end of the war-game replication. See Figure 6.

3.6. Measure of Effectiveness. To analyze the CE in a simulation model, we used the BSR as a measure of effectiveness indicating the level of capability to win in a battle. The BSR and red survival ratio (RSR) are calculated as follows.

Initially, the remaining assets (B_T/R_T) are calculated at the end of engagement for both sides.

Next, they are compared with the initial assets (B_0/R_0), and their ratios are counted for both sides.

Hence, the BSR and RSR were calculated by

$$BSR = \frac{B_T}{B_0} \times 100,$$
$$RSR = \frac{R_T}{R_0} \times 100 \quad (1)$$

The BSR and RSR represent the ratio of survival assets compared to its corresponding original assets. In other words, they are merely the blue survival ratio and red survival ratio after the battle has completed. The condition of the battle termination is supposed to be predefined before the simulation is run.

4. Output Analysis

4.1. Communication Failure and Terrain Maps Are Considered. The path loss functions in Table 1 are used to consider the CEE within an engagement model. According to the distance between the agents, the CSP is determined as shown in Figure 7. The X-axis depicts the distance between agents, and the Y-axis depicts the communication power arriving at the RX. The threshold (depending upon the value of K in

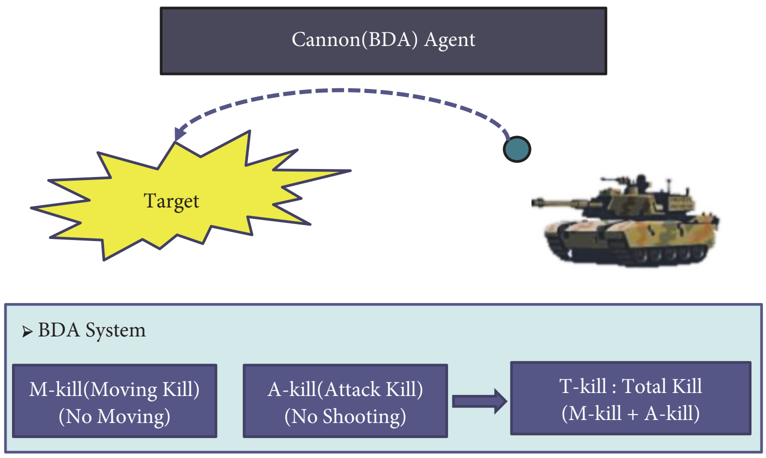

FIGURE 6: Role and process of BDA agent.

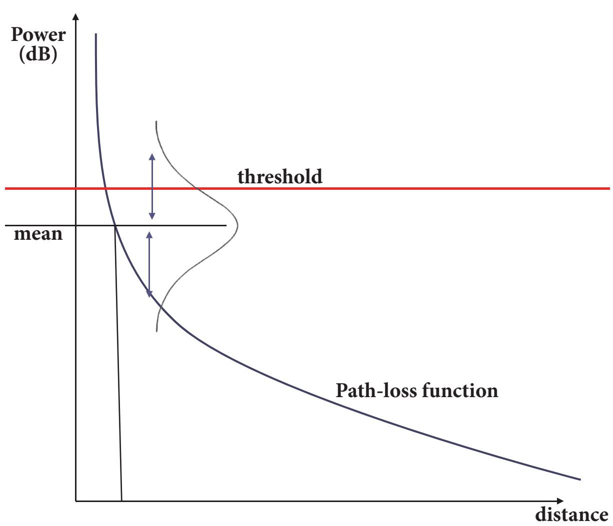

FIGURE 7: Path loss function and threshold to decide CSP.

TABLE 3: Two cases for terrain condition.

Cases	Blue Force	Red Force
Case-1 Simplified Digital Map	K: 1, 0.5, 0, -0.5	K: 1
Case-2 Commercial Digital Map	K: 1, 0.5, 0, -0.5	K: 1

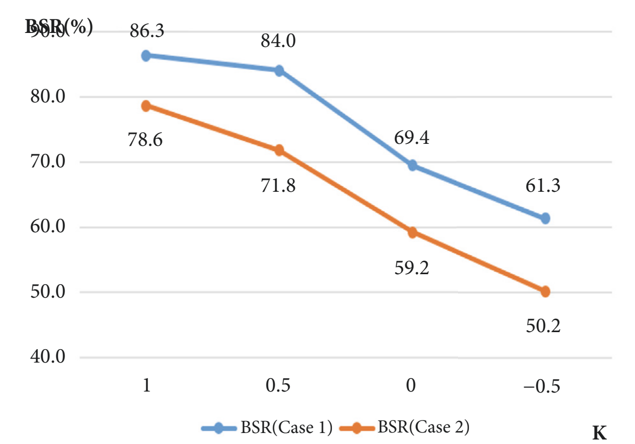

FIGURE 8: BSR comparison depending upon both CSP and terrain condition.

(2)) represents the minimum communication power that the RX can recognize. It also signifies the receiver's performance capability to obtain the signal power. Hence, a larger K value renders a lower threshold, thus providing a higher probability of communication success. Meanwhile, the smaller value of K produces a lower probability of communication success.

$$Threshold = -(K \times \sigma) + mean\,(dB) \qquad -3 \leq K \leq 3 \tag{2}$$

To assess the relationship trend depending upon the level of LOS, terrain maps are also considered in two cases of both the simplified and commercial cases, as shown in Table 3. Case 1 provides more room for a higher probability of LOS than Case 2.

Figure 8 shows the different values of the BSR for both Case 1 and Case 2 and its changing trend over the level of performance capability of the RX.

Based on this experiment, it is clear that more room for the LOS and the high quality of the RX provide a better MOE value (BSR) of the CE. In this particular scenario, Case 1 demonstrates a 7.7%–12.2% higher BSR value than Case 2.

4.2. Alternative Measure Considered. To compensate and overcome communication failure, a typical measure was performed. In other words, a communication repeater is added whenever communication failure occurs. In the model, we assumed that all the blue unit's platforms serve as a communication repeater. Three scenarios are established, as shown in Table 4.

In Scenario 1, the terrain condition is clear and the LOS will function at all times. In Scenario 2, however, the LOS

Table 4: Three scenarios for different LOS and Non-LOS(NLOS) conditions.

Scenario	Scenario-#1	Scenario-#2	Scenario-#3
Situation	Communication in only LOS situation	Communication in LOS / NLOS situation	Communication using Communication Repeater in LOS / NLOS situation

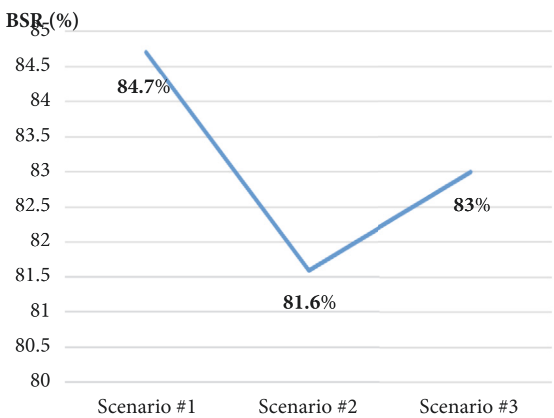

Figure 9: BSR comparison depending upon communication repeater.

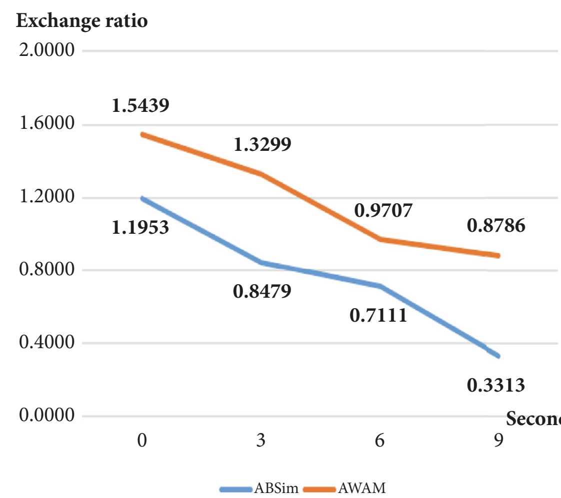

Figure 10: Comparison of both models depending upon time delay owing to communication failure.

would be blocked and would depend on the terrain condition where both the TX and RX are located. Scenario 3 is the same as Scenario 2 but with a communication repeater.

Figure 9 shows the different values of BSR among the three scenarios. The MOE value of Scenario 1 is the highest while that of Scenario 2 is the lowest and that of Scenario 3 is somewhere in between that of scenarios 1 and 2. This experiment shows the quantitative effectiveness of the new measure of using a communication repeater when the CSP value is poor.

We can also apply this result to decide whether to purchase a communication repeater by performing a cost benefit analysis. Based on this assessment approach, more valuable information will be obtained such as the optimal number of communication repeaters and the optimal level of CSP to add a communication repeater.

4.3. Validation of the Model Performed. An issue in the simulation approach is the validation problem to verify for fitting to the real-world situation. To perform model validation, we use the AWAM and compare its result to those from our model called "ABSim." The AWAM is the most popular and powerful analytic tool for both the US and Korean Army.

The validation process is as follows:

(1) Establish a scenario

(2) Build the input data

(3) Perform the experiment

(4) Compare the results

To create the same environment for fair comparison for both models (AWAM and ABSim), input data such as the initial assets for the blue and red forces are the same, and the output performance is measured as an exchange ratio. Additionally, we change the time delay owing to communication failure at every 3 seconds and compare the result values of exchange ratio. The exchange ratio is the number of red forces for one unit of blue forces. For the blue side, the larger exchange ratio is better.

Figure 10 shows the values of exchange ratio depending upon the time delay owing to the communication failure of both models. A gap exists between the results of the two models, but it is fairly consistent over the time delay within a certain range.

According to many subject matter experts (SMEs), we found three reasons to create a gap between two models.

(1) The AWAM uses confidential data such as probability of detection, and probability of hit, which are not opened to the public; therefore, ABSim had to use assumed data referenced by the SME.

(2) A gap exists in the level of fidelity on the terrain map for both models.

(3) Different tactics are used for moving and the tactical behaviors for both models.

Many SMEs reported that reasons above can compensate for the gap shown in Figure 10 between two models.

5. Conclusion

We proposed a new simulation process considering communication failure in a network-centric warfare environment. To measure the quantitative CE in a network-based battlefield, we consider both the CEE and LOS depending upon the altitude of the terrain cell.

The MOE values obtained from the model we developed indicated that the LOS and CEE were highly correlated to each other. This implies that a clear LOS scenario obtains a higher BSR (we used MOE) value compared to the NLOS situation.

We also demonstrated the effectiveness when the communication repeater was applied during communication failure. This may provide insight into the method to obtain the optimal policy for adapting the communication repeater, such as the optimal number or optimal time to add a communication repeater.

Finally, we compared the simulation results from our model to the one from AWAM and found that both results were fairly consistent.

We came to a conclusion that communication failure is one of the key factors and has to be kept in good condition for whole engagement process in a network-centric operational environment.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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