The Capacity Analysis of the Orthogonal Frequency Hopping Stacked Nets in the Data Link

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Abstract. The Link-16 can support stacked nets mode for the Joint Tactical Information Distribution System (JTIDS) uses orthogonal frequency hopping networking. The Link-16 can support 127 stacked nets in theory. The number of stacked nets is restricted to 20 in the United States Navy. There are few studies about the impact of the number of stacked nets to the performance. The number of stacked nets has important aspects to network design and planning of data link. Through analysing the architecture of stacked nets, the mathematical model about frequency conflict between sub-networks is established. Under different slot structure, the influences of average delivery are simulated. The simulation results can support the network programming of data link.

1. Introduction

Data link is a tactical information system which adapts to the needs of modern warfare and the development of information technology and is used for data transmission and exchange between command and control systems, sensors and weapon platforms. It takes wireless channel as the main transmission medium and formatted information transmission and processing as the main purpose. It completes the information system needed for specific battle/tactics cooperation among command and control system, sensors and weapon platforms. It plays an important role in improving the command ability of joint operations and giving play to the effectiveness of weapon platforms.

Link-16 is the preferred tactical data link for command, control and intelligence of the US Defence Department. Its JTIDS (Joint Tactical Information Distribution System) terminal uses frequency hopping orthogonal networking to support cascade mode of work. It can organize 20 stacked nets in the same area without interference, effectively expanding the capacity of JTIDS network. According to the available data, JTIDS can support 127 stacked nets in its network space, but considering the possible interference between the networks, the US military has limited the use of only 20 stacked nets. However, there is no literatures analysis on why to limit the number of stacked nets and how to determine it. Based on the study of the structure of stacked nets in JTIDS, this paper establishes a mathematical model of frequency conflict between subnets, and on this basis, simulates and verifies the key performance indicators such as network capacity and packet loss rate under different slot load factors, which provides a basis for data link network planning and design. [1,2,3,4]
2. Stacked Nets in Link-16
The terminal of a single JTIDS network divides 24 hours a day into 112.5 time units, each of which is 12.8 minutes. Each time unit is further divided into 98304 slots, each of which is 7.8125 milliseconds. Time slot is the basic unit to access JTIDS network. JTIDS network uses TDMA communication system to realize multiple simultaneous running communication networks. In order to enhance the anti-jamming performance, Link-16 synthesizes frequency hopping, RS coding and CCSK direct sequence spread spectrum and other technical measures.[5,6,7,8]

2.1. Frequency Hopping and Slot Structure
There are 51 radio frequency carrier frequencies in JTIDS, frequency hopping every 13 microseconds. Data is transmitted in a time slot in the form of a series of pulse symbol packets carrying messages. Pulse is divided into single-pulse and double-pulse. The symbol packet length of a single-pulse is exactly equal to the dwell time of frequency hopping (13 microseconds), that means, one pulse is sent at each frequency point. In data encapsulation, there are three ways to choose: standard packed (3 words per group), double-packed (6 words per group) and four-packed (12 words per group). Standard packed is always transmitted in a double-pulse structure. Double-packed can be either single-pulse or double-pulse structure. Four-packed is always transmitted in a single-pulse structure.

2.2. RS Coding
The fixed format message of JTIDS uses RS coding to detect and correct errors. 16 symbol error detection and correction codes are added to the data of 15 symbols (5 bits per symbol) in the message, and the valid data of 15 symbols is transformed into 31 symbols. The coding method can detect and correct up to eight symbol errors, which are generally expressed in (31,15).

2.3. CCSK DSSS
The data transmitted by JTIDS is first encoded by RS, then mapped to symbols, interleaved and processed by CCSK. Each 5-bit symbol is represented as a 32-bit sequence in which the bits are called chips. According to the analysis of literature [6], CCSK can correct up to 6 chip errors when decoding with correlation values. After more than 6 errors, the corresponding sequence cannot be selected according to the correlation value.

2.4. Stacked Nets
Stacked nets can be "stacked" by 128 JTIDS networks. As shown in Figure 1, each JTIDS network uses a specific frequency hopping pattern. In practice, up to 20 stacked nets have been set up in the same region at the same time. There are no relevant literatures on the reasons. This paper will analyse stacked nets, and simulate the relationship between the average receiving rate and the number of stacked nets, which will provide a basis for the selection of the number of Stacked Nets.

3. Model of Stacked Nets Collision
This paper studies the staked nets structure of JTIDS. Event-driven method is used to build JTIDS simulation model. The main events include slot start, symbol sending and symbol arrival.

3.1. Processes of Sending, Receiving and Dealing with the Network Data

3.1.1. Frequency hopping mode. A symbol corresponds to a pulse transmission at a frequency point. Each transmission uses a different working frequency, that is, frequency hopping mode. According to the selected working mode, the number of pulses that have been sent is recorded.

3.1.2. Arrival events. According to the distance between receiving nodes, different arrival events are generated.
3.1.3. **Dealing with the data.** When a symbol arrives, the receiving node records the number, frequency and symbol network number of the received signals, and then calculates the corresponding bit error rate. Definition $S_n$ for the currently received symbol, $S_t$ for the target symbol, $T_d$ for the time difference between $S_n$ and the correct received symbol, $T_m$ for the duration of $S_n$ and the maximum overlap time of the allowable symbol, $T_r$ for the duration of $S_n$ and the recently received symbols of the same frequency, $f_c$ for the correct frequency of received symbols, $N_{en}$ for the symbol network number, $N_{nn}$ for the network number of the node.

1. If $T_d < T_m$, then $S_n$ isn’t $S_t$ in the same network. If it’s similar with $f_c$, it is regarded as noise interference. If the bit error rate exceeds the error correction capability of the terminal, it is a conflict.
2. If $T_d > T_m$, and $N_{en} = N_{nn}$, The current symbol is $S_t$.
3. If $T_r < T_m$, then there is conflict between symbols, it will be judged as non-conflict.
4. Using RS error-correcting codes, every 31 symbols are detected once. If the number of wrong symbols is less than or equal to 8, all 31 symbols are considered correct, otherwise only the conflict-free symbols are correctly received.

### 3.2. Pulse Conflict

Whether a pulse is effectively jammed or not is defined as: when a pulse overlaps more than 1.4 microseconds in time with the same frequency as other subnets (CCSK’s code distance is 14 and the maximum number of error correction bits is 7), the pulse is considered to be effectively jammed. For overlapping symbols in time domain, the possible overlap range is 13 microseconds, where the size of the interference duration is 10 microseconds, as shown in Figure 2.

The probability of conflict between two symbols in time domain is $\frac{10}{13}$. The condition of no conflict between receiving node and a symbol is that there is no conflict in frequency domain, then the probability is $\frac{50}{51}$, or $(\frac{1}{51}) \ast (\frac{3}{13})$ in time domain. Assuming that the number of stacked nets is $N$, the probability that the receiving node does not conflict with $N-1$ symbol is as follows:

$$P(N-1) = \left(\frac{50}{51} + \frac{3}{51+13}\right)^{N-1} = \left(\frac{653}{663}\right)^{N-1}$$

(1)

If there is no RS coding error correction, then one message is successfully received depend on 31 symbols are correctly received before, the probability is as follows:

$$\left(\frac{653}{663}\right)^{N-1} \ast 31$$

(2)

With RS coding error correction, 31 symbols can be judged as a correct message if they can receive more than or equal to 23 symbols correctly, and the probability is as follows:

$$\sum_{i=23}^{31} C_i^{31} \left(\frac{653}{663}\right)^{N-1} \ast \left(1 - \frac{653}{663}\right)^{N-1} \ast (31-i)$$

(3)
3.3. Symbol Strength
The simulation only considers the conflict in time domain and frequency domain. On the basis of the simulation model, symbol strength and RS coding error correction are added to optimize the model, so that the simulation effect is closer to the actual situation. The uniformly distributed random number function is used to randomly distribute all nodes in a circle with a radius of 150 kilometres, to generate a fully connected simulation network topology, and to simulate and calculate the propagation loss of radio waves in free space.

In the simulation, the power of JTIDS terminal is 200 watt, according to the formula of free space radio wave propagation loss \( L = 32.4 + 20 \log f + 20 \log d \) (DB), it calculates the received power at the time of receiving. Other symbols received in the time of receiving the local network symbols are regarded as noise and the signal-to-noise ratio is calculated. According to the formula of reference [5], the symbol error probability of CCSK under different SNR conditions can be obtained in Figure 3. Then the receiver performance of JTIDS terminal is simulated by random function. If the symbol error probability exceeds the terminal error correction ability, the symbol conflict is determined.

4. Results and Analysis
Under different conditions such as the number of stacked nets, factor of slot load, slot mode of operation and the number of nodes, the number of symbols sent by all nodes of a single stacked nets, the number of maximum received symbols, the maximum received rate and the average received rate are counted during the simulation time, and the results are analysed. In the theoretical result curve, the impact of signal-to-noise ratio (SNR) is not considered in the impulse conflict, but SNR is added in the simulation calculation to make it closer to the actual channel. The simulation results are as follows.
4.1. Symbol Receiving Rate

In Figure 4, with the increase of the number of stacked nets, the theoretical curve of the average reception rate of symbols shows a linear downward trend, and the simulation results show a downward trend as a whole, floating up and down near the theoretical values. Therefore, it can be considered that the simulation results are basically consistent with the theoretical values, thus proving the correctness of the simulation model.

4.2. Standard Packed Mode

4.3. Dual-packed Mode
4.4. Four-packed Mode

![Figure 9](image9.png)  ![Figure 10](image10.png)

Figure 9. The relationship between the average receiving rate of four-packed messages without RS code and the number of stacked nets

Figure 10. The relationship between the average receiving rate of four-packed messages with RS code and the number of stacked nets

From the simulation data, it can be concluded that the average receipt rate of messages is independent of the time slot mode of operation. The average receipt rate of messages is shown in Table 1 when the number of stacked nets is different and whether RS coding error is corrected or not.

| Number of Stacked Nets | Error Correction without RS Coding | Error Correction with RS Coding |
|------------------------|-----------------------------------|---------------------------------|
|                        | Theoretical value | Simulation value | Theoretical value | Simulation value |
| 5                      | 0.094830          | 0.069830           | 0.976260          | 0.952626          |
| 10                     | 0.008993          | 0.008193           | 0.835727          | 0.952626          |
| 15                     | 0.000853          | 0.000803           | 0.835727          | 0.831727          |
| 20                     | 0.000081          | 0.000071           | 0.573247          | 0.533247          |
| 25                     | 0.000008          | 0.000007           | 0.314733          | 0.304733          |

5. Conclusion

The simulation results show that error correction using RS coding can greatly improve the average receiving rate of messages. Without RS coding, communication can hardly work properly. With the increase of the number of stacked nets, the average receiving rate of messages decreases gradually. The simulation results show that when the number of stacked nets reaches 15, the average receiving rate of messages is 83.2%, and when the number of stacked nets reaches 20, the average receiving rate of messages decreases to 53.3%. If the number of stacked nets continues to increase, the average message reception rate drops rapidly. When the number of stacked nets reaches 25, the average message reception rate is only 30.4%. At this time, communication reliability is very low, and it is difficult to meet the requirements of wartime command information transmission. Therefore, when using JTIDS, the U.S. military can only use 20 stacked nets at the same time. This paper only analyses the reliability of symbol transmission under ALOHA protocol, without considering the access control mechanism of MAC protocol. In the follow-up study, we can consider the joint simulation of physical layer and MAC layer, simulate SHUMA protocol, and analyse the performance of different channel access control protocols under single and multi-network conditions in high-speed frequency hopping network.

6. References

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