AN EXPLOITATION OF TUFTE'S SMALL MULTIPLES

Carl T. Russell
Colorado Springs, Colorado

ABSTRACT

The Theater Missile Defense System Exerciser (TMDSE) is a large geographically-distributed simulation developed by the Missile Defense Agency (MDA). TMDSE is used to investigate Joint Data Network (JDN) interoperability between the members of the terminal-phase theater Family of Systems (FoS) as they develop. In this paper, SAS and PowerPoint are used to exploit Tufte's notion of small multiples ("graphics can be shrunk way down") for analyzing the communication time delays (communications latencies) inherent to the simulated JDN message traffic. This paper shows how simple statistical graphics implemented on a modern laser printer can produce comprehensive, easily understood characterizations of such communications latencies for 100,000 or more data points.*

.

INTRODUCTION

The theater missile defense Family of Systems (FoS) is comprised of many systems at varying levels. The complete FoS has systems at the early warning sensor level, the weapon and sensor level, and the command and control level, see Figure 1. For this full FoS to operate as efficiently as possible, the various systems within each level and across levels need to be interoperable. To achieve this interoperability, each system has to implement the appropriate information exchange protocols, and within the specific protocol, the appropriate messages.

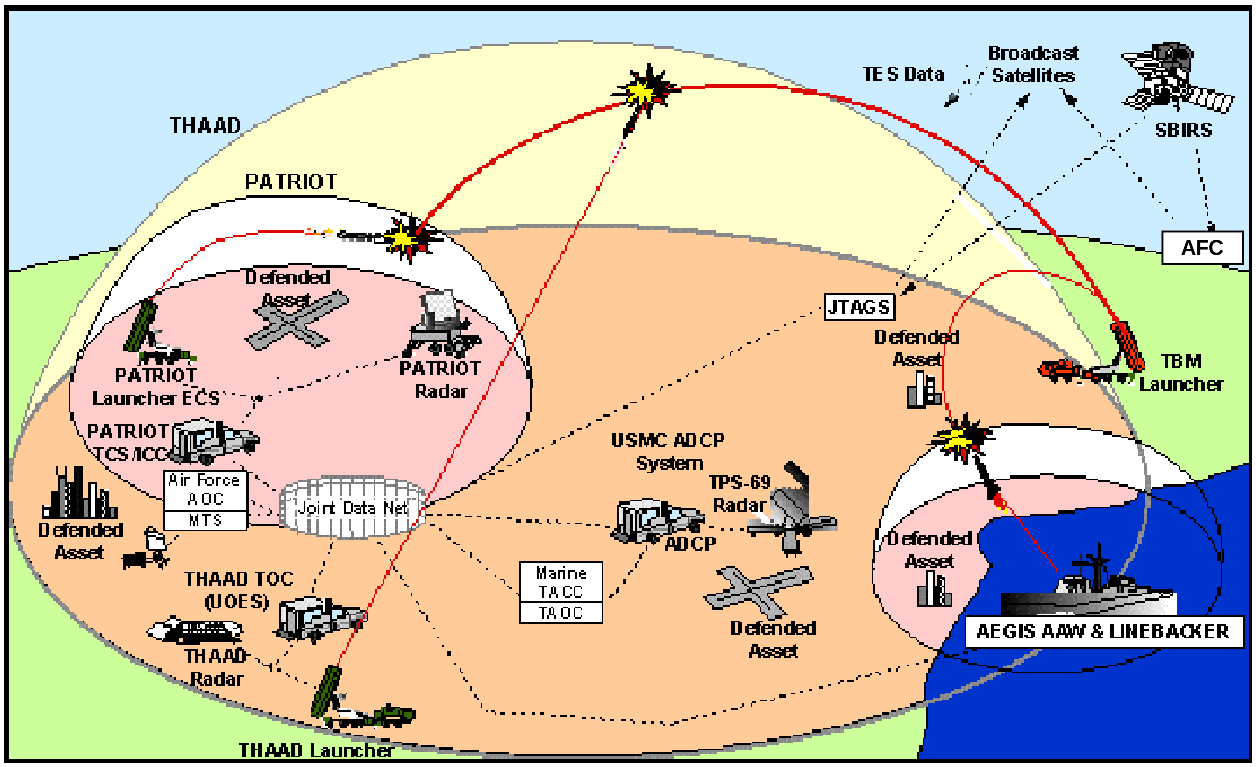


Figure 1. Theater Missile Defense Family of Systems Architecture.

The Theater Missile Defense System Exerciser (TMDSE) is a large geographically-distributed hardware-in-the-loop (HWIL) simulation developed by the Missile Defense Agency (MDA). The tactical segments participating in a recent TMDSE HWIL test were as follows:

- Early warning sensor level
  - U.S. Army Joint Tactical Ground Station (JTAGS)
  - U.S. Air Force Aerospace Fusion Center (AFC)

* Although this paper was cleared for open publication by MDA on October 4, 2000, this is not an official government paper.

- Weapon and sensor level
  - U.S. Navy AEGIS LINEBACKER
  - U.S. Army Theater High Altitude Area Defense (THAAD)
  - U.S. Army Phased Array Tracking to Intercept of Target (PATRIOT), both Post-Deployment Build (PDB) -4 and PDB-5
- Command and control level
  - U.S. Air Force Theater Air Command and Control Simulation Facility (TACCSF), Control and Reporting Center (CRC) (Missile Tracking System [MTS] only)
  - U.S. Marine Corps (USMC) Tactical Air Operations Center (TAOC), Air Defense Communication Platform (ADCP) and TPS-59 only
  - U.S. Navy AEGIS Anti-Air Warfare (AAW)

Geographical locations of these tactical segments are shown in Figure 2. TMDSE stimulates current or future versions of tactical segments by providing a simulated threat environment and communications connectivity.

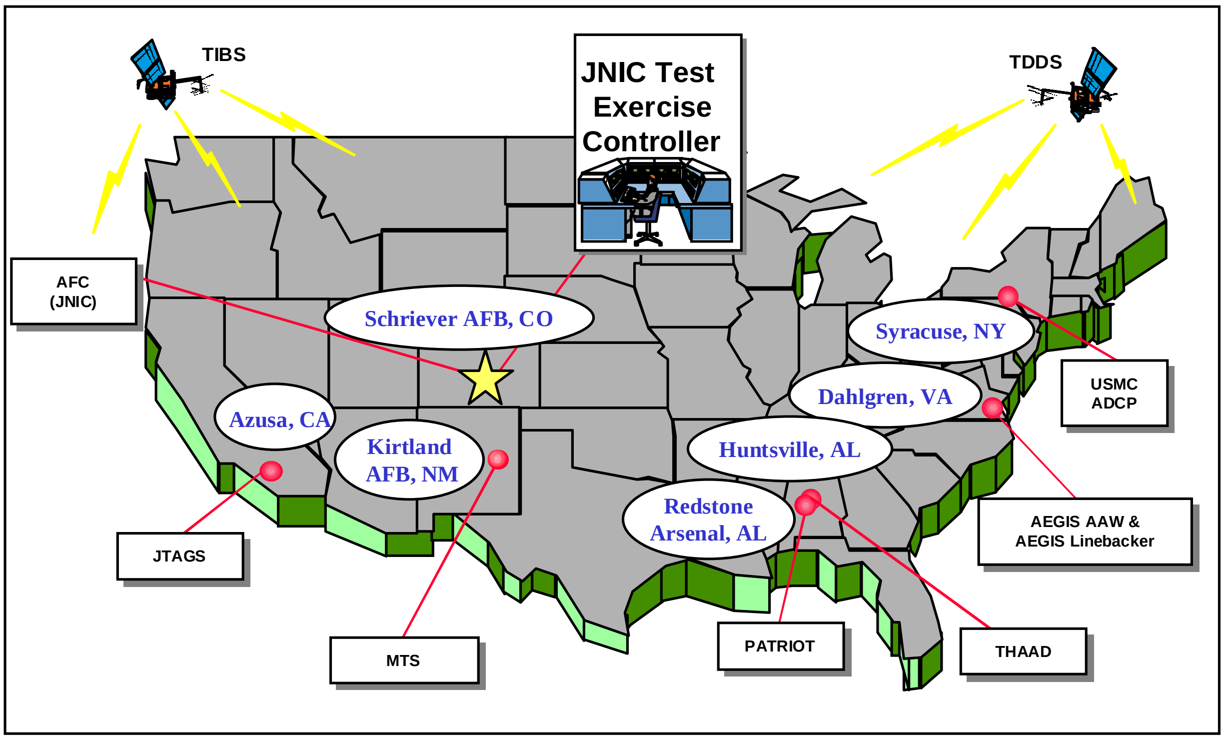


Figure 2. Geographical Location of TMDSE Tactical Segments.

The Joint Data Network (JDN) is a subset of the total FoS communications structure, and it provides the supporting communications architecture. Figure 3 depicts the TMDSE test architecture used. TMDSE is comprised of the TMDSE Control Segment (TCS), the Tactical Communications Environment Segment (TCES), and the Remote Environments (REs). The TCS is comprised of the TEC located at the JNTF and REs located with the Tactical Driver Segments (TDSs). The TCS controls and stimulates the environment within which the TMD FoS operates and provides overall control and coordination of the TMDSE system for testing. The TCS provides the physical interface and functional capabilities to interface with each of the Tactical Drivers (TDs) and the TCES Link-16 Gateways, which emulate the JDN communications networks.

TMDSE and the participating tactical nodes exchange environment information (ground truth information such as time space position information (TSPI) on Theater Ballistic Missiles (TBMs) and TMD interceptors) using Distributed Interactive Simulation (DIS) Protocol Data Units (PDUs). The tactical nodes exchange JDN messages via TCES. The TCES emulates a Joint Tactical Information Distribution System (JTIDS) network for Tactical Digital Information Link (TADIL)–J messages over dedicated T-1 landlines and provides a backup capability for the Tactical Information Broadcast Service (TIBS) and TRAP (Tactical Receiver and Related Applications) Data Dissemination System (TDDS) messages. The primary route for TIBS and TDDS messages is through a live

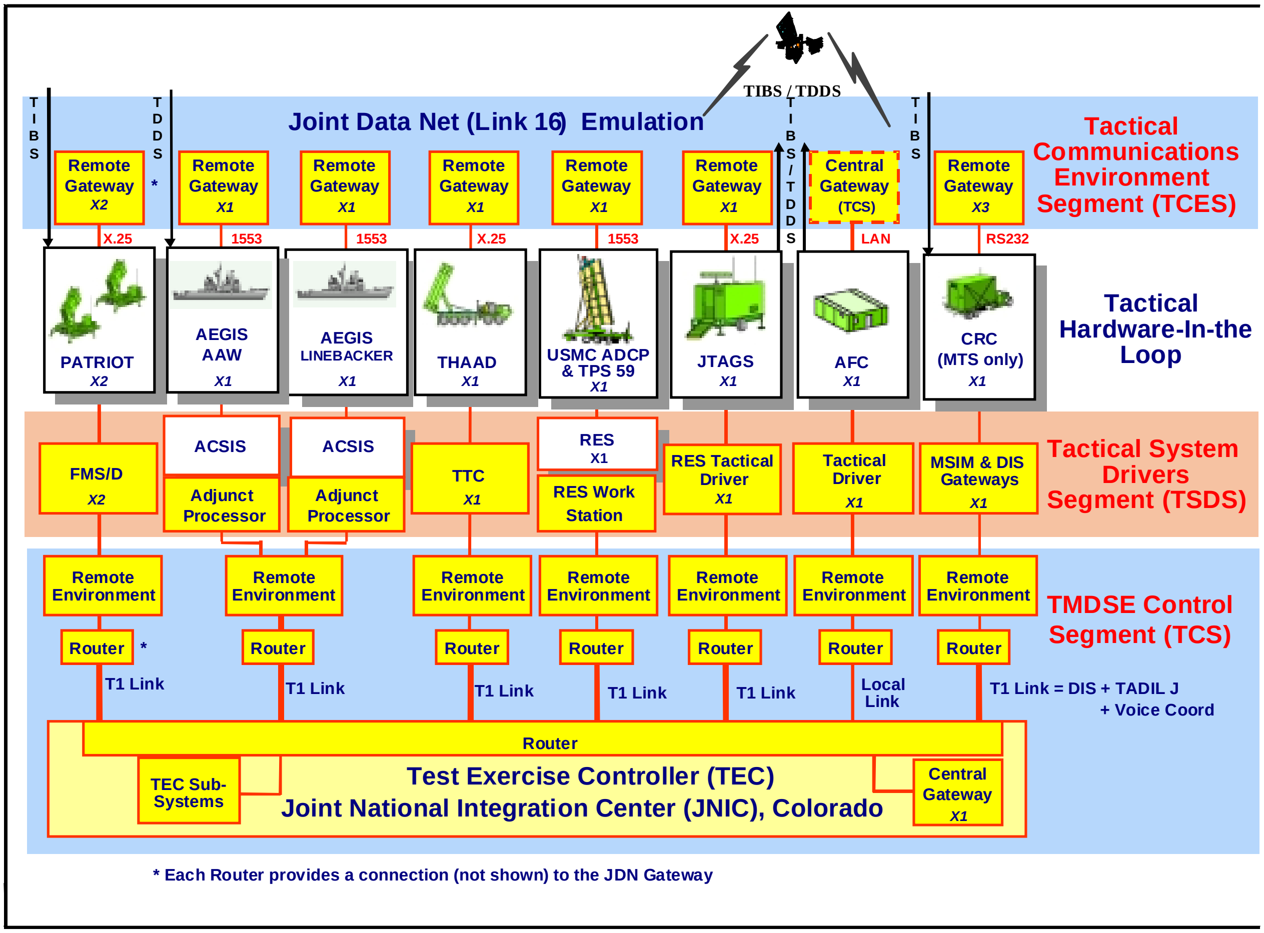


Figure 3. TMDSE Test Architecture.

Satellite Communications (SATCOM) feed; the secondary route is via TCES over a dedicated T-1 landline. Positioning of the TMDSE segments (simulated locations on the virtual battlefield) and launches of threat TBMs are scripted according to an approved scenario, but responses to those threat launches is via the distributed segment simulators and TADIL-J messages over the surrogate JDN.

COMMUNICATIONS LATENCY IN TMDSE

Among the issues addressed during testing was communications latency within TMDSE. Messages were recorded and time-stamped at the transmitting node and its corresponding gateway as well as at receiving gateways and nodes. After matching each sent message with its receipts, latencies could be calculated throughout the system for each receipt. Of course some messages could not be matched end-to-end, and some messages were probably mismatched. Table 1 gives for five key types of TADIL-J message receipts the number of messages for which latencies could be calculated (by location of receipt for each test run of interest). Possible dependence of latencies on transmitting and receiving segments are also of interest, but since not all message types were recorded at all segments, the effects of transmitting and receiving segments are nested within message type. Considering all 1143 factor combinations (including transmitting and receiving node), the range of sample sizes per factor combination is extreme, as shown by the summary in Figure 4. The overall sample sizes are so large that using simple linear modeling to understand trends breaks down because everything is statistically significant. This is shown by the ANOVA in Table 2 for a simple linear model of latencies from transmitting node to receiving node. Moreover, detailed tables of latency summaries are unwieldy, stretching to several hundred pages. Fortunately, it is not difficult to display the latency data graphically in a way that makes meaningful analysis clear.

GRAPHICAL APPROACH TO OVERALL TRANSMITTING-NODE-TO-RECEIVING-NODE LATENCIES

Boxplots provide an effective way to display latencies by transmitting segment, message type, and receiving segment as in Figure 5 (80 percent boxplots are used: whiskers stretch from the 10^{th} to the 25^{th} percentile and 75^{th}

Table 1. Key TADIL-J Messages for Latency Calculation, by Location, Message Type and Test Run.

Location of Received Message	**Message Type**	**Number of Messages for Latency Calculation**		
		Test Run I	**Test Run II**	**Test Run III**
Transmitting Gateway	**a**	2126	2033	1774
	b	1072	973	976
	c	478	528	507
	d	124	95	166
	e	1210	1324	1831
Receiving Gateway	**a**	17668	16640	15884
	b	8584	7664	8014
	c	3802	4220	4174
	d	981	745	1300
	e	9619	10524	14562
Receiving Node	**a**	12755	12229	12352
	b	6474	5817	6341
	c	3802	3062	3181
	d	981	529	974
	e	5964	6141	8803

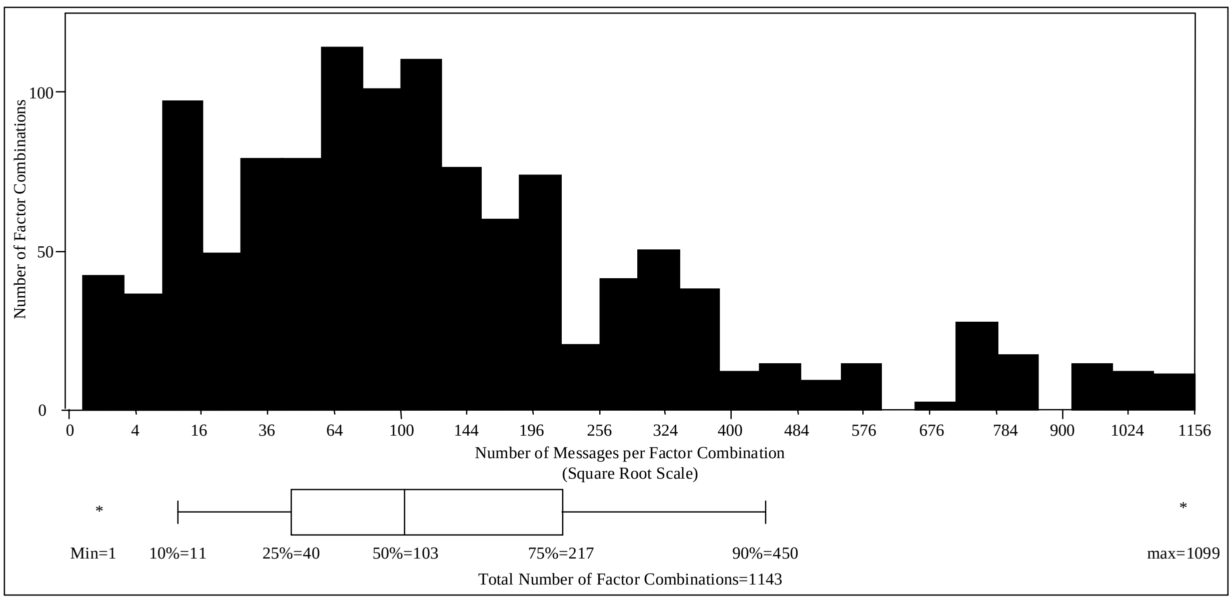


Figure 4. Distribution of Number of Messages per Factor Combination.

Table 2. Analysis of Variance for a Simple Model (Everything Is Statistically Significant)

Source	**DF**	**F Ratio**	**Prob>F**
Test Run	2	529.2	<0.0001
Message Type	4	63.8	<0.0001
Test Run x MsgType	8	8.5	<0.0001
Transmitter	7	1897.4	0.0000
Receiver	6	19.8	<0.0001
Test Run x Transmitter	14	196.9	0.0000
Test Run x Receiver	12	5.2	<0.0001

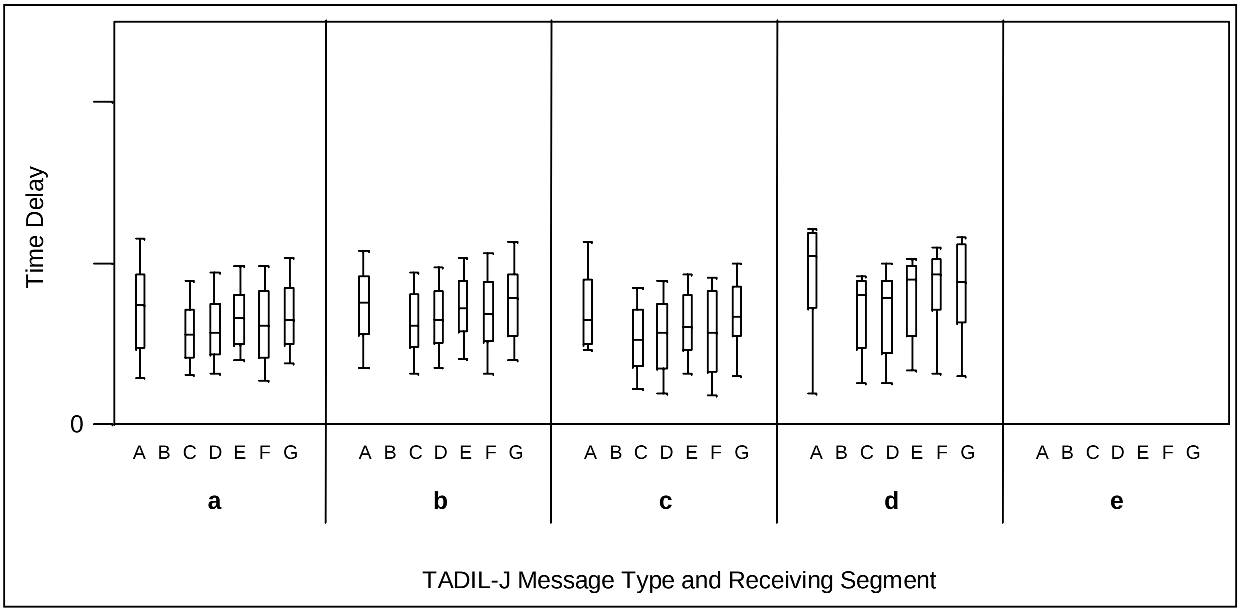


Figure 5. Time Delays for Key Messages Transmitted by Segment “B” on Test Run I,
by Message Type and Receiving Segment.

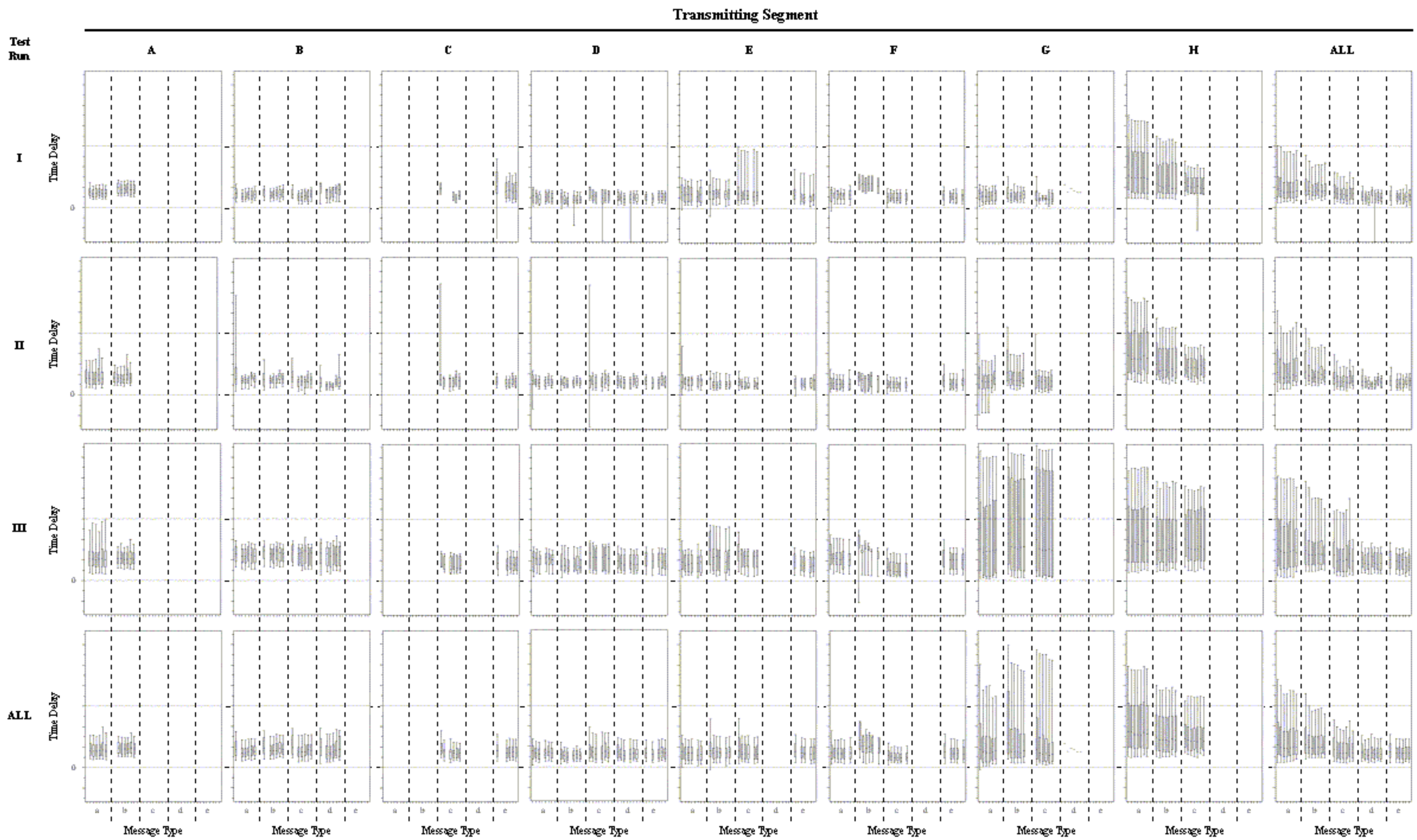
percentile to 90th percentile of the latency distribution for each receiving segment; the 50th percentile is marked with a horizontal line). Missing data for segment “B” with all message types is due to the fact the segment “B” is transmitting the messages and therefore has no latency distribution. Missing data for all receiving segments with message type “e” is due to the fact that segment “B” does not transmit message type “e.” Shrinking Figure 5, repeating it for each transmitting segment on each test run, and arranging the resulting displays in a tabular fashion gives Figure 6. Figure 6 is even more effective when printed on tabloid-sized paper, but it is still usable on letter-sized paper. Patterns of messages not present at certain segments are clear as is the overall stability of latencies. Close examination of Figure 6 reveals many apparent small trends but few appear to be substantial. Most of these small trends, including the suspicious long whiskers, are due to the small sample sizes identified in Figure 4, and these can be easily tabulated. Three larger trends stand out but will not be discussed in detail here.

GRAPHICAL DECOMPOSITION OF TRANSMITTING-NODE-TO-RECEIVING-NODE LATENCIES

For each Test Run in Figure 6 (first three rows) the transmitting-node-to-receiving-node latencies can be decomposed into three parts: time delays from transmitting node to transmitting gateway, time delays from transmitting gateway to receiving gateway (this is where the geographical distribution is, but T1 lines are being used), and time delays from receiving gateway to receiving node. This is done in Figures 7-9 which show that almost all the transmitting node to receiving node latencies is due to time delays from the transmitting nodes to the transmitting node gateways and that time delays from transmitting gateways to receiving gateways are negligible. Counting the summary transmitting-node-to-receiving-node rows in Figures 7-9 separately, Figures 7-9 concisely summarize more than 300,000 data points in a much more useful fashion than any table or analysis of variance could possibly do.

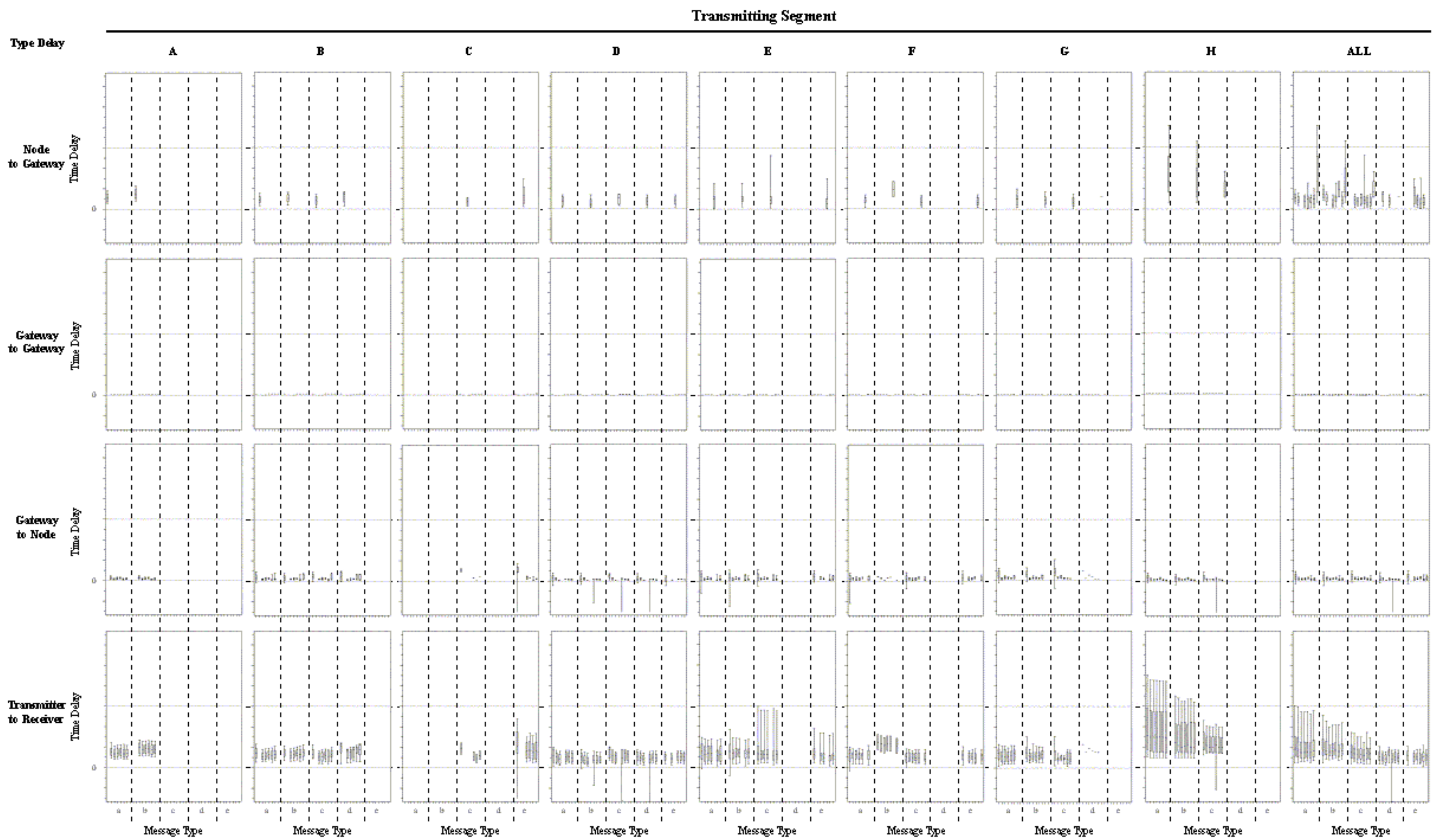
GRAPHICAL ADJUSTMENT FOR APPARENT NODE CLOCK ERRORS

Data in Figures 5-9 have actually been adjusted for apparent errors in clock synchronization at nodes “E”-“H” on some test runs. Figure 10, analogous to Figure 6 but without any adjustment, shows obvious systematic anomalies in the unadjusted data. There are clearly no serious synchronization problems between gateways since unadjusted time delays between gateways in Figures 7-9 are so small. The unadjusted gateway-to-node time delays in Figure 11 show consistent differences between time delays at “A”-“D” and those at “E”-“G.” These permit approximate graphical estimates of what clock adjustments should be. The unadjusted node-to-gateway time delays in Figure 12 provide a check on the Figure 11 estimates and give additional estimates for segment “H” adjustment. (Several computational methods to determine appropriate adjustments were also attempted, but the graphical method worked best.)



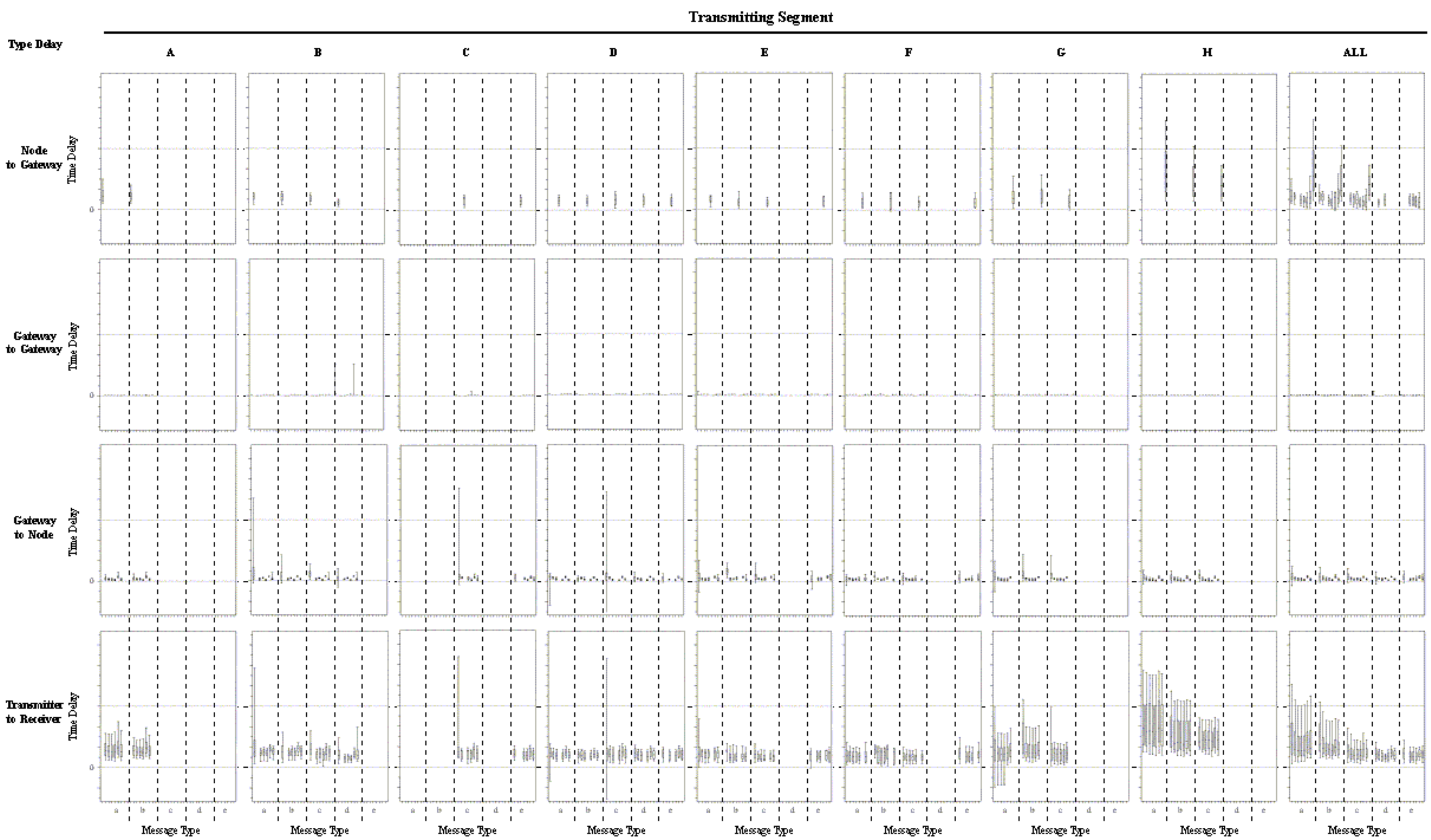
Within message type, the "whiskers" on the boxplots extend from the 10th to the 25th percentile and the 75th to the 90th percentile of the latency distribution for each receiving segment; the 50th percentile (median) is marked with a horizontal line.
Within message type, left to right receiving segment order is: A, B, C, D, E, F, G.
Delays corresponding to Segment H node receipts are not displayed, and the sending node for each cell has no receiving latency distribution except node to gateway.

Figure 6. Transmit to Receive Time Delays by Test Run, Transmitting Segment, Message Type and Receiving Segment (80% Boxplots). Times Adjusted for Apparent Node Clock Errors.



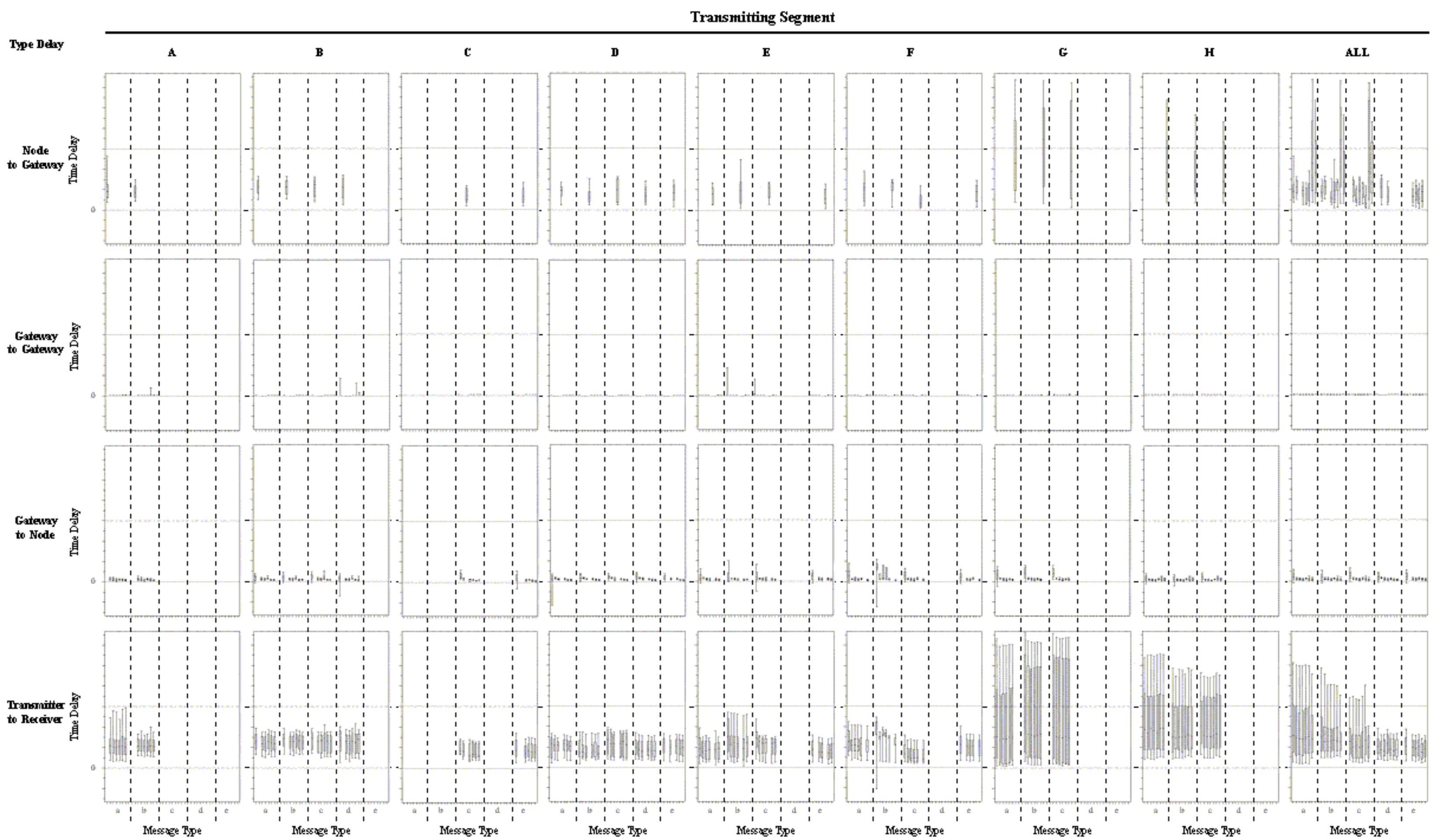
Within message type, the "whiskers" on the boxplots extend from the 10th to the 25th percentile and the 75th to the 90th percentile of the latency distribution for each receiving segment; the 50th percentile (median) is marked with a horizontal line.
Within message type, left to right receiving segment order is: A, B, C, D, E, F, G.
Delays corresponding to Segment H node receipts are not displayed, and the sending node for each cell has no receiving latency distribution except node to gateway.

Figure 7. Time Delays on Run I by Type Delay, Transmitting Segment, Message Type and Receiving Segment (80% Boxplots). Times Adjusted for Apparent Node Clock Errors.



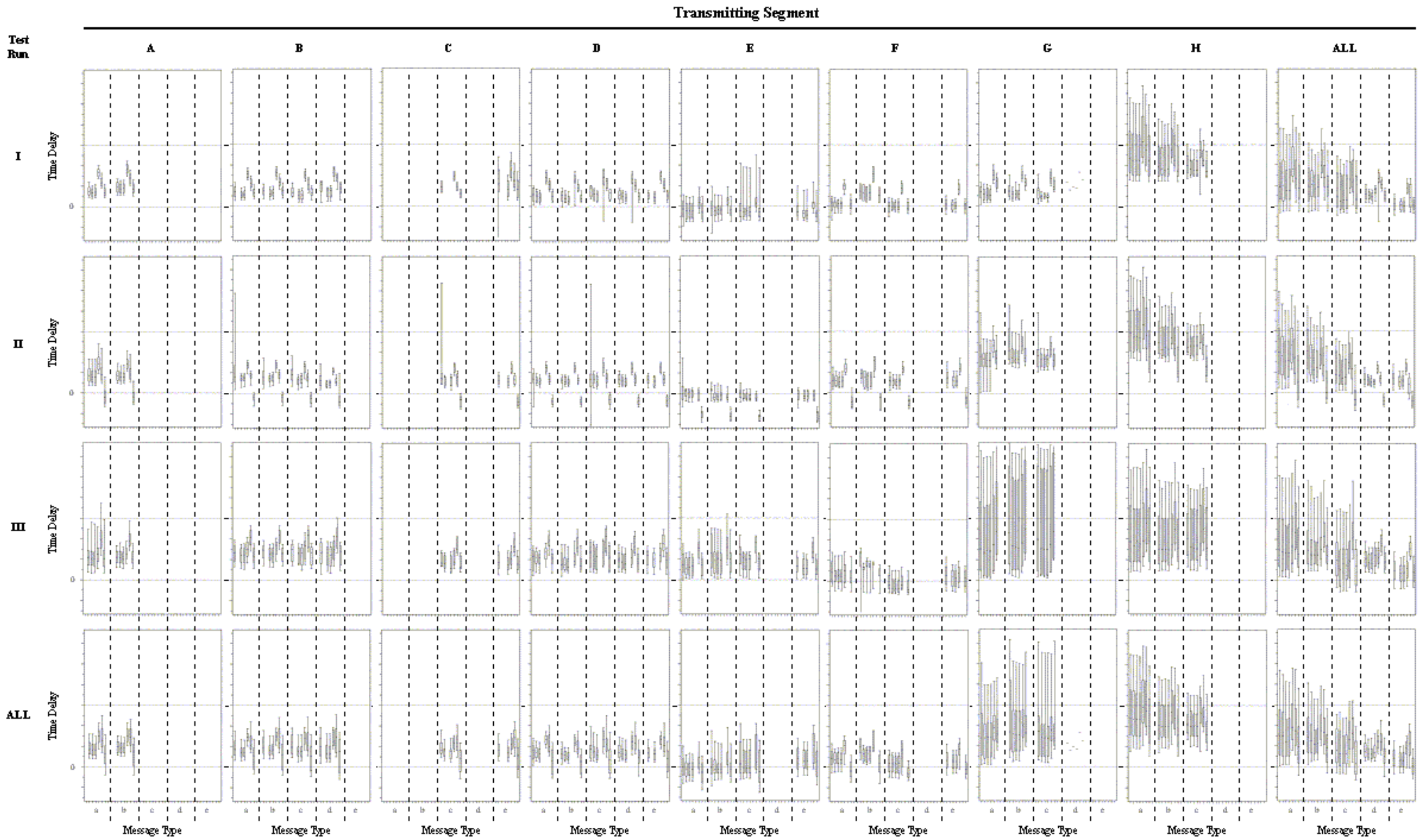
Within message type, the "whiskers" on the boxplots extend from the 10th to the 25th percentile and the 75th to the 90th percentile of the latency distribution for each receiving segment; the 50th percentile (median) is marked with a horizontal line.
Within message type, left to right receiving segment order is: A, B, C, D, E, F, G.
Delays corresponding to Segment H node receipts are not displayed, and the sending node for each cell has no receiving latency distribution except node to gateway.

Figure 8. Time Delays on Run II by Type Delay, Transmitting Segment, Message Type and Receiving Segment (80% Boxplots). Times Adjusted for Apparent Node Clock Errors.



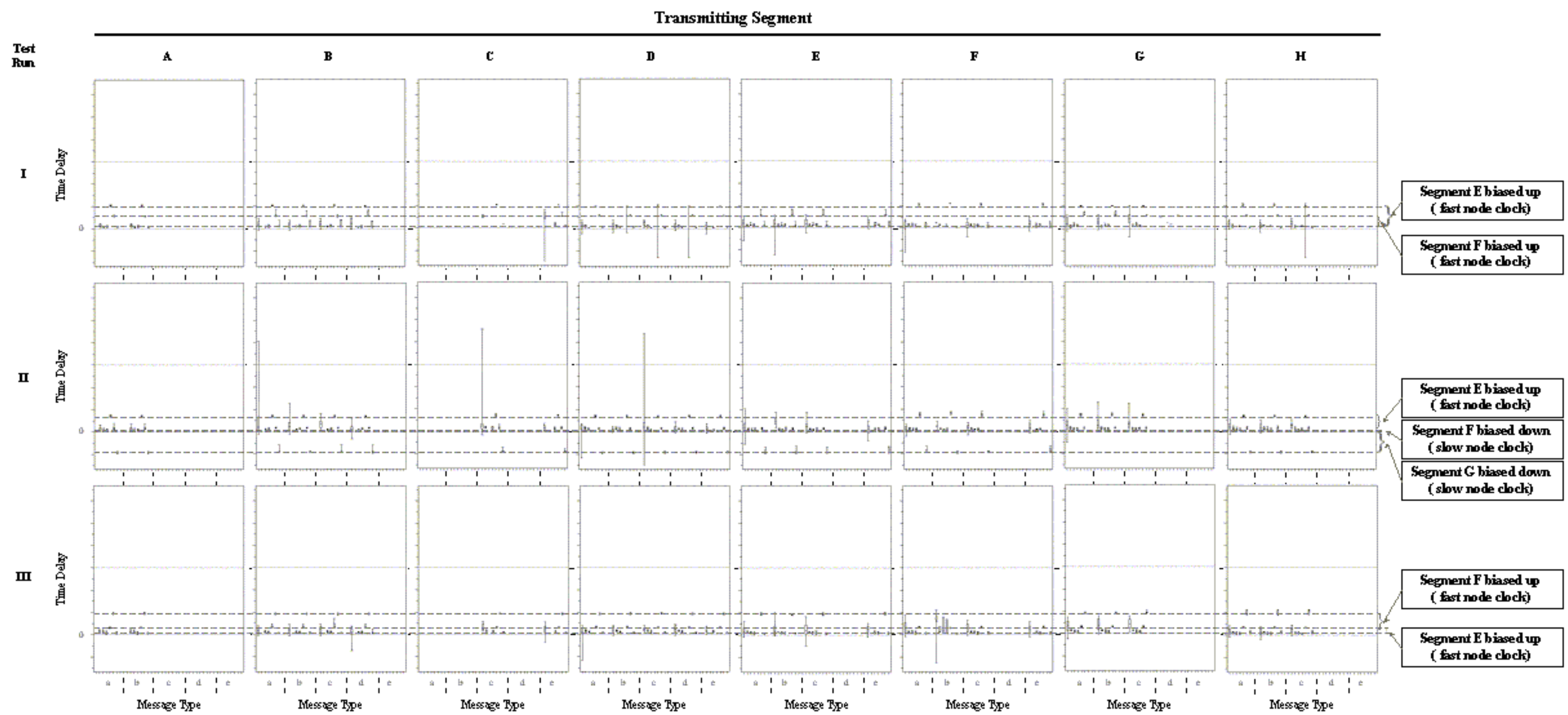
Within message type, the "whiskers" on the boxplots extend from the 10th to the 25th percentile and the 75th to the 90th percentile of the latency distribution for each receiving segment; the 50th percentile (median) is marked with a horizontal line.
Within message type, left to right receiving segment order is: A, B, C, D, E, F, G.
Delays corresponding to Segment H node receipts are not displayed, and the sending node for each cell has no receiving latency distribution except node to gateway.

Figure 9. Time Delays on Run III by Type Delay, Transmitting Segment, Message Type and Receiving Segment (80% Boxplots). Times Adjusted for Apparent Node Clock Errors.



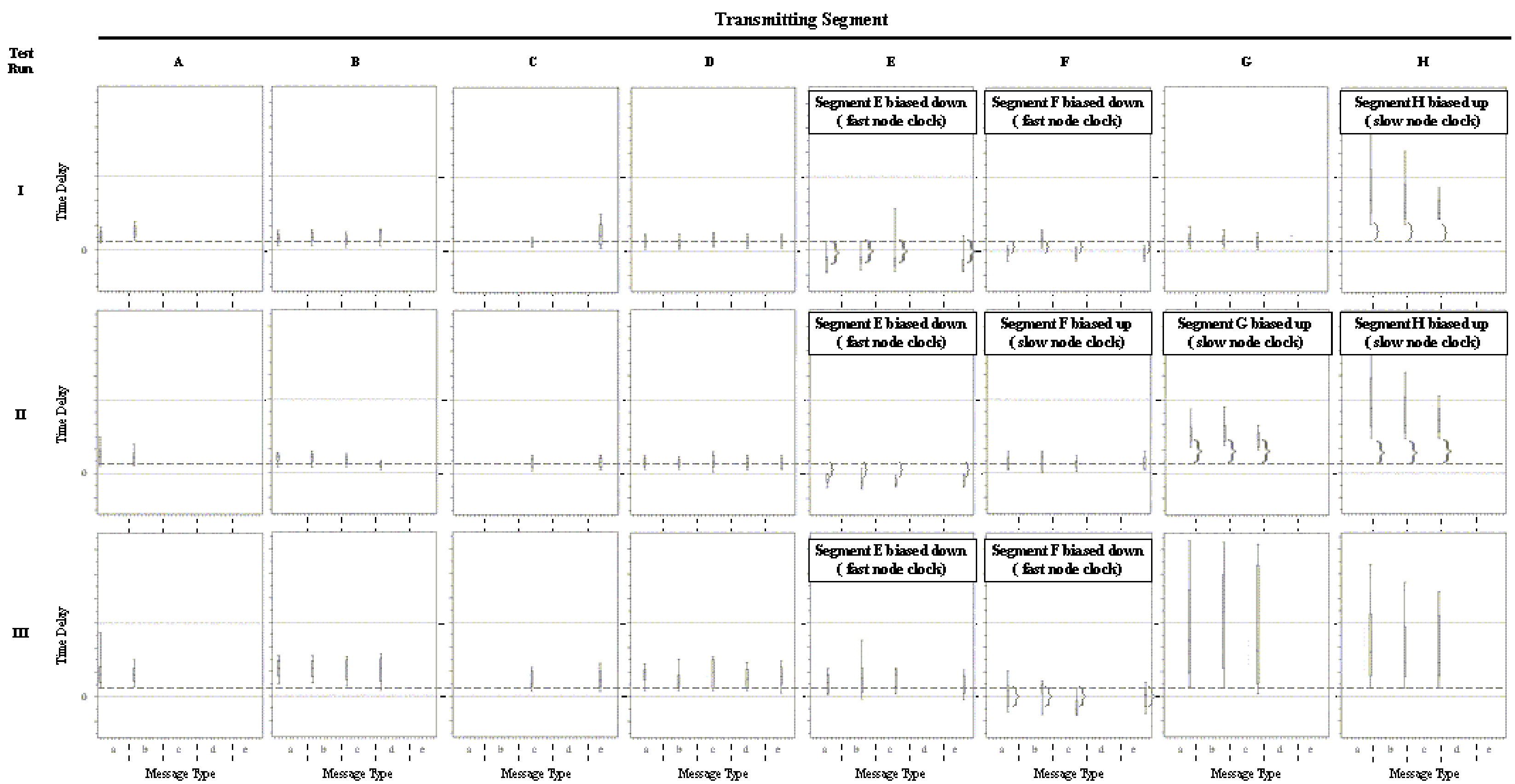
Within message type, the "whiskers" on the boxplots extend from the 10th to the 25th percentile and the 75th to the 90th percentile of the latency distribution for each receiving segment; the 50th percentile (median) is marked with a horizontal line.
Within message type, left to right receiving segment order is: A, B, C, D, E, F, G.
Delays corresponding to Segment H node receipts are not displayed, and the sending node for each cell has no receiving latency distribution except node to gateway.

Figure 10. Transmit to Receive Time Delays by Test Run, Transmitting Segment, Message Type and Receiving Segment (80% Boxplots). Times Not Adjusted for Apparent Node Clock Errors.



Within message type, the "whiskers" on the boxplots extend from the 10th to the 25th percentile and the 75th to the 90th percentile of the latency distribution for each receiving segment; the 50th percentile (median) is marked with a horizontal line.
Within message type, left to right receiving segment order is : A, B, C, D, E, F, G.
Delays corresponding to Segment H node receipts are not displayed, and the sending node for each cell has no receiving latency distribution except node to gateway.

Figure 11. Gateway to Node Time Delays by Test Run, Type, Transmitting Segment, Message Type and Receiving Segment (80% Boxplots). Times Not Adjusted for Apparent Node Clock Errors.



Within message type, the "whiskers" on the boxplots extend from the 10th to the 25th percentile and the 75th to the 90th percentile of the latency distribution for each receiving segment; the 50th percentile (median) is marked with a horizontal line

Figure 12. Node to Gateway Time Delays by Test Run, Type, Transmitting Segment, Message Type and Receiving Segment (80% Boxplots). Times Not Adjusted for Apparent Node Clock Errors.

SUMMARY

This paper has shown how simple statistical graphics—miniaturized and implemented on a modern printer (1200 dots per inch with tabloid paper capability)—can produce rich, easily understood analyses of large data sets. Such graphical techniques have not yet been much used in DoD analyses, but similar techniques have been frequently exploited by in other fields and as the following brief discussion indicates.

Tukey's "Orange Book"[1] popularized the boxplot and ignited a continuing emphasis on the graphical side of statistics, and his 1993[2] paper provided new insights on boxplots and other aspects of statistical graphics. Tufte's three extraordinary books[3,4,5] broadened the audience for clear quantitative display. Among many other insights, Tufte tauted the ability of the human eye to make "a remarkable number of distinctions within a small area" and promoted high "data density" ("number of entries in data matrix" ÷ "area of data graphic") and the use of small multiples ("graphics can be shrunk way down") as in this paper. Three bullets of three words each per PowerPoint slide is a more standard goal for DoD briefings, and high data densities typically face stiff resistance. This is true even though the densest common quantitative graphic—a map—is readily understood. More efforts like the one in this paper may gain wider acceptance of dense graphics in DoD. Display of graphics panels in tabular form has been common for some time in the form of scatterplot matrices (now available in most statistics packages) and more recently in trellis displays,[6] but the tabular displays used here have more in common with recent graphical data mining techniques[7,8,9,10,11] than with trellis displays.

REFERENCES

1. Tukey, J.W. Exploratory Data Analysis. Reading: 1977.
2. Tukey, J.W. "Graphical Comparisons of Several Linked Aspects: Alternatives and Suggested Principles." Journal of Computational and Graphical Statistics, vol. 2 nbr. 1, pp. 1-49, 1993.
3. Tufte, E.R. The Visual Display of Quantitative Information. Cheshire, Connecticut: 1983, pp161-175.
4. Tufte, E.R. Envisioning Information. Cheshire, Connecticut: 1990, pp. 67-79
5. Tufte, E.R. Visual Explanations. Cheshire, Connecticut: 1997.
6. Becker, R.A., Cleveland, W.S. and Shyu, M-J. "The Visual Design and Control of Trellis Display." Journal of Computational and Graphical Statistics, vol. 5 nbr. 12 pp. 123-155, 1996.
7. Church, K.W. and Helfman, J.I. "Dotplot: A Program for Exploring Self-Similarity in Millions of Lines of Text and Code." Journal of Computational and Graphical Statistics, vol. 2 nbr. 2, pp. 153-174, 1993.
8. Eick, S.G. "Graphically Displaying Text." Journal of Computational and Graphical Statistics, vol. 3 nbr. 2, pp. 127-142, 1994.
9. Becker, R.A., Clark, L.A. and Lambert, D. "Cave Plots: A Graphical Technique for Comparing Time Series." Journal of Computational and Graphical Statistics, vol. 3 nbr. 3, pp. 277-283, 1994.
10. Keim, D.A. "Pixel-Oriented Visualization Techniques for Exploring Very Large Data Bases." Journal of Computational and Graphical Statistics, vol. 5 nbr. 1, pp. 58-77, 1996.
11. Fayyad, U.M. and Smyth P. "Cataloging and Mining Massive Datasets for Science Data Analysis." Journal of Computational and Graphical Statistics, vol. 8 nbr. 3, pp. 589-610, 1999.