Electronic Town Meeting Voting Investigation

Grafton Information Technology Committee
May 13, 2019

Executive Summary

In October 2015, the Town of Grafton began using an electronic voting system for Town Meetings. The Town initially acquired a system consisting of 500 handheld wireless keypads ("clickers") and one base station, using it successfully through October 2017, with no indication that the system failed to count all votes cast. The Town then expanded the system by adding 172 keypads and a second base station, using it successfully in February 2018, but in May 2018 and again in October 2018, it became clear partway through Town Meeting that the system was not counting all votes.

Following the October 2018 Town Meeting, the Town of Grafton Information Technology Committee undertook to investigate the failures in May and October of 2018. The objective of the investigation was to determine the cause of those failures and determine what actions, if any, the Town can take to ensure that the system can be used reliably in future Town Meetings.

A series of tests was performed, the result of which was to identify the causes and contributors to the failures:

- The primary cause of the May and October 2018 failures was inadequate separation between the two base stations.
- The assignment of the original 500 keypads to the smaller of the two base stations exacerbated the failures, because the majority of the keypads were attempting to communicate with that base station and many were failing due to interference from the larger and more powerful base station.
- Many of the original keypads were reporting weak batteries; the weak batteries were not the root cause of the failures, but were likely to have increased the number of keypads that failed.

We recommend the following to ensure reliable performance at future Town Meetings:

- Place the base stations six feet apart.
- Place base stations so that there are no obstacles between them and the audience.
- Configure the WRS970 (the larger base station) to Channel 1 (the original 500 keypads) and the WRS971 (the smaller base station) to Channel 8 (the added 172 keypads).
- Use a powered USB hub.
- Replace keypad batteries every two years.
- Clearly instruct Town Meeting voters to pay attention to the light on the keypad, to retry the vote if a red light flashes, and to request a replacement keypad if the red light flashes again.
- To test the system at the beginning of Town Meeting, collect the count of checked-in voters from the PollPads, instruct voters to press a button (doesn't matter which one), and verify that the vote count is close to the number of checked-in voters (expect a difference of maybe ten or so, due to voters that check in but do not get keypads, are out of the room at the time, or are not paying attention).

1. Introduction

In October 2015, the Town of Grafton began using an electronic voting system for Town Meetings. Through February 2018, that system was used successfully for six Town Meetings, with no indication that the system failed to count all votes cast. In May 2018, and again in October 2018, it became clear partway through Town Meeting that the system was not counting all votes.

Following the October 2018 Town Meeting, the Town of Grafton Information Technology Committee undertook to investigate the failures in May and October of 2018. The objective of the investigation was to determine the cause of those failures and determine what actions, if any, the Town can take to ensure that the system can be used reliably in future Town Meetings.

The investigation was able to identify the reason for the system failures and explain how the failures can be avoided. In this report, we describe the electronic voting system and its past use in Town Meetings, explain the testing procedures and results, and provide recommendations for the continued use of the system.

2. Background

2.1 Grafton's Use of Electronic Voting for Town Meeting

Grafton's first use of the electronic voting system, which is a set of handheld wireless keypads ("clickers") and a base station, was at the October 2015 Annual Town Meeting. The system used was on loan from the vendor, and was used as a demonstration of that system for Town Meeting voting.

Based on the successful use at that Town Meeting, Grafton proceeded to purchase a system with 500 keypads. That system (the *original system*) was first used in May 2016.

At the May 2017 Town Meeting, the attendance of 632 exceeded the system's capacity of 500, and thus the system could not be used. In anticipation of future meetings of this size, Grafton added 172 keypads to the system. This system (the *expanded system*) was first used in February 2018.

Table 1 lists the eight Town Meetings at which the electronic voting system was used, along with data, where available, describing the performance of the system. The voting data in Table 1 is drawn from Table 2, which shows each vote counted by the electronic voting system for every Town Meeting at which the system was used and for which we obtained the count of votes for each vote taken. Note the following:

- The number of voters checked in always exceeds the number of votes recorded, because not all checked-in voters participate in the voting.
- The number of votes recorded per vote taken varies from one vote to the next (it is not mandatory that every voter cast a vote on every vote taken, and the number of voters in the auditorium varies during the meeting).
- The data for the May Town Meetings combines the Special and Annual Town Meetings held on those dates.
- A numeric record of the voting results for the October 2015 and May 2016 meetings was not available (the moderator announced the outcome of each vote, but not in terms of the number of votes in favor and opposed).

- Use of the keypad system was discontinued partway into the May 2017 meeting when the attendance grew beyond the number of available keypads.
- Use of the keypad system was discontinued partway into the May and October 2018 meetings when it became clear that the system was not recording all votes cast.

Table 1: Town Meetings Using Keypad System

Meeting date	Keypad system used	Number of warrant articles	Number of votes taken with keypads	Number of voters checked in	Average number of votes recorded per vote taken	Average % of checked-in voters recorded as voting
10/19/15	Loaner	28	28			
05/09/16	Original	60	60			
10/17/16	Original	17	17	128	111	87%
05/08/17	Original	52	14	632	328	52%
10/16/17	Original	44	45	169	138	82%
02/12/18	Expanded	7	8	125	113	90%
05/14/18	Expanded	43	19	182	115	63%
10/15/18	Expanded	26	17	154	58	38%

Table 2: Votes Taken Using Keypad System

	Original System				Expanded System		
	10/17/16	05/08/17	10/16/17		02/12/18	05/14/18	10/15/18
# of check-ins	128	632	169		125	182	154
# of votes	17	14	45		8	19	17
Maximum count per vote	117	388	155		119	147	74
Average count per vote	111	328	138		113	115	58
Minimum count per vote	104	257	110		102	95	40
Count of votes recorded for each vote taken (abstentions not included)	104	257	147	135	102	99	74
	111	281	154	145	108	104	71
	115	295	155	144	116	110	70
	115	302	151	138	119	105	66
	108	286	153	137	116	110	64
	114	318	142	136	119	114	64
	114	322	146	136	109	108	64
	107	322	148	126	114	110	62
	109	335	148	139		133	57
	110	375	148	130		105	58
	108	370	148	140		131	55
	113	370	143	129		134	53
	108	372	141	134		129	43
	117	388	144	138		132	49
	106		136	130		106	61
	112		137	129		111	40
	113		140	131		147	41
			144	129		95	
			143	127		95	
			142	110			
			138	116			
			144	116			
			133				

2.2 System Description

The electronic voting system was purchased from Audience Response Systems, Inc. (audienceresponse.com) of Evansville, Indiana. It consists of a set of handheld keypads that wirelessly transmit votes through a base station to a software application on a laptop computer. The software application collects the votes and displays the results.

In this system, a single base station can communicate with up to 500 keypads. To accommodate audiences in excess of 500, an additional base station is required for each additional set of up to 500 keypads. The association between keypad and base station is made by assigning a channel number to a base station and that same channel number to the keypads that are to communicate with that base station. Each keypad has an address (1-500) that is unique on its channel.

The wireless communication between keypad and base station utilizes a frequency-hopping spread-spectrum radio technology operating in the 2.4 GHz band. The base station polls each keypad individually, repeating the poll every second or two while votes are being collected (i.e. while voting is "open"). When a voter presses a key on the keypad, the keypad responds to the next poll it receives by transmitting the keypress to the base station, which forwards the keypress to the software application. When the application receives the keypress, it causes the base station to transmit an acknowledgment to the keypad. The keypad is thus able to confirm that the vote has been successfully counted, and if the keypad fails to receive an acknowledgement after a certain period of time, it will indicate that failure to the voter by flashing a red light. While the keypad is attempting to transmit the keypress, it flashes a green light.

The original system consisted of the following components:

- 500 model WRS7100 keypads configured to Channel 1
- One model WRS971 base station configured to Channel 1
- The WRS971 base station and a software key device were both plugged into USB ports on a laptop running the *SNAP-ARS* software application

The expanded system consists of the following components:

- 500 model WRS7100 keypads configured to Channel 1 (the original keypads)
- 172 model WRS7100 keypads configured to Channel 8 (the new keypads)
- One model WRS971 base station (new)
- One model WRS970 base station (new)
- The default configuration assigns Channel 1 to the WRS971 and Channel 8 to the WRS970; this default configuration has been used in all Town Meetings to date
- The two base stations and a software key device are plugged into an unpowered USB hub which in turn is plugged into a USB port on a laptop running the *ARS Pro* software application

The components of the system (room size and power figures are from the manufacturer's literature):

WRS970	Large base station (see Figure 1); box (roughly 5" x 6") form factor; USB cable connection; accommodates a room up to 650' x 650'; 300 mA maximum USB current draw
WRS971	Small base station (see Figure 2); USB stick form factor; accommodates a room up to 300' x 300'; 50 mA maximum USB current draw

Software key	Sentinel HASP (Hardware Against Software Piracy) (see Figure 3); small USB stick form factor; authorizes software application for a specific set of keypads and base stations
WRS7100	Keypad (see Figure 4) with buttons for the digits 0-9, four additional buttons for special functions, and green and red lights; form factor similar to an automobile key fob

The manufacturer's description of the capacity and current draw of the two base stations implies that the WRS970 is significantly more powerful than the WRS971. The physical size difference between the two tends to support this notion.

The keypads in each set of up to 500 WRS7100 keypads are numbered 1 through 500, corresponding to the address mentioned above. The keypad number is printed on the keypad's label. This means that, in a case like Grafton's where more than one set of keypads is used, two or more keypads may have the same number. To distinguish among keypads, the appearance of the label is distinctly different for each set of keypads. Figure 4 shows the different labels in Grafton's two sets of keypads.

Figure 5 shows the unpowered USB hub that Grafton has been using to connect the software key and the two base stations to a laptop computer. The placement of the three devices in the ports on the hub is not critical; they could be placed in any order.

Figure 1: WRS970 Base Station

Figure 2: WRS971 Base Station

Figure 3: Sentinel HASP Software Key

Figure 4: WRS7100 Keypad
(L to R) Front, Original (Channel 1) Back, New (Channel 8) Back

Figure 5: USB Hub With (L to R)
Cable to WRS970, WRS971 and HASP

3. Keypad System Testing

The Information Technology Committee performed a series of tests, with the following objectives:

1. Determine the cause of the poor performance observed in May and October 2018.
2. Determine what actions, if any, can be taken to ensure that the system can be used reliably in future Town Meetings.

There are many potential explanations for the poor performance. The best way to find the correct explanation is to find a way to reproduce the failures at will, under conditions that closely replicate the Town Meeting environment. Only by doing so, and then identifying a specific cause, making a change corresponding to that cause, and observing that with that one change the problem goes away, can we be sure that we have understood and know how to solve the problem.

3.1 Inventory and Status of Keypads Used in October 2018

The set of keypads used in the October 2018 Town Meeting were set aside after that meeting, in anticipation of a possible future investigation into the failures experienced at that meeting. It was thus possible for this investigation to begin with an inventory and basic operation check of the specific keypads involved in the most recent failures.

Table 3 summarizes the results of this inventory. Every one of the keypads was operated one or more times in close proximity to the base stations while observing the keypad responses in the diagnostic map of the ARS Pro application. That map consists of an array that shows the status of every configured keypad, and for each keypad it shows the key, if any, that was pressed and highlights that keypad in yellow if the keypad reported a low battery status when the key was pressed (see Figure 5).

Table 3: Keypad Inventory and Initial Check Status

Group	Subgroup	Number Received	Low Battery	Good Battery
Channel 1 (original set)	**1-100**			
	101-200	31	4	27
	201-300	16	2	14
	301-400	53	45	8
	401-500	31	29	2
Channel 8 (new set)	**1-100**	1	0	1
	101-172	10	0	10
Totals		142	80	62

The fact that more than 50% of the keypads (all from the original set) used in the October 2018 Town Meeting reported weak batteries in this check suggested the possibility that weak batteries might be an explanation for the failures. Thus, further testing to determine the effect of weak batteries on the system performance was indicated.

Figure 5: Keypad Map

During the initial check test, it was observed that in many cases a keypad that reported a low battery subsequently reported a good battery after being operated repeatedly. The number of repetitions before a good battery was reported varied, but often a single repetition resulted in the battery status being reported as good.

In order to identify a set of keypads that would consistently report weak batteries, at least on the first keypress, a subset of keypads from the original set was tested on two occasions, several days apart. On each occasion, each keypad was operated repeatedly until a good battery status was reported, and the number of operations required was noted. Table 4 is a record of this test, which identified 14 keypads that could reliably produce a weak battery status on at least the first keypress.

Table 4: Identification of Keypads Consistently Reporting Weak Batteries

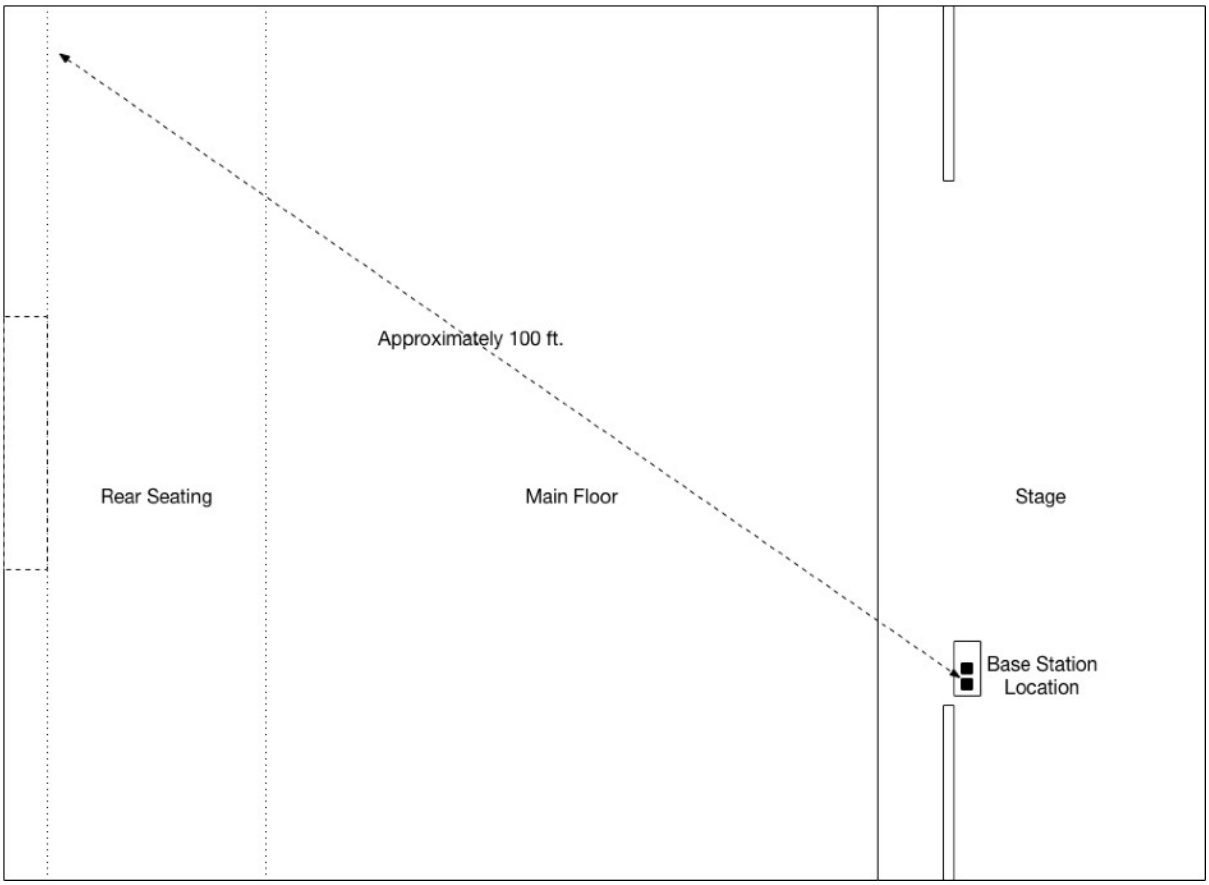
Keypad #	Test 1 repetitions	Test 2 repetitions	Outcome	Consistently good	Consistently weak
161	1	1	Consistently good	161	
169	1	1	Consistently good	169	
173	1	1	Consistently good	173	
174	1	1	Consistently good	174	
186	9	1	Inconsistent		
187	1	1	Consistently good	187	
188	3	2	Consistently weak		188
194	1	1	Consistently good	194	
196	2	2	Consistently weak		196
197	1	1	Consistently good	197	
212	1	1	Consistently good	212	
226	1	1	Consistently good	226	
305	2	2	Consistently weak		305
309	7	3	Consistently weak		309
310	3	3	Consistently weak		310
319	2	2	Consistently weak		319
340	2	2	Consistently weak		340
344	2	2	Consistently weak		344
349	3	2	Consistently weak		349
402	1	2	Inconsistent		
404	1	3	Inconsistent		
406	4	2	Consistently weak		406
408	2	2	Consistently weak		408
422	2	2	Consistently weak		422
423	2	2	Consistently weak		423
424	1	2	Inconsistent		
429	1	2	Inconsistent		
444	2	2	Consistently weak		444
446	1	2	Inconsistent		
Number of consistent keypads				9	14

3.2 Testing at a Distance

3.2.1 Town Meeting Location

Town Meetings are held in the Grafton High School auditorium, with the keypad system base stations located on the stage and the keypads distributed in the seating around the auditorium. This obviously means that some keypads are located close to the base stations and others are quite far away. The auditorium seating area (from the front edge of the stage to the rear of the room) is more or less a square, approximately 80 feet on each side, with the stage on one side. The stage opening facing the audience is approximately 48 feet wide. With the keypad system base stations located on a table at one end of that stage opening, the distance to the seat farthest away (on a diagonal, and accounting for the height at the rear) is approximately 100 feet. See Figure 6.

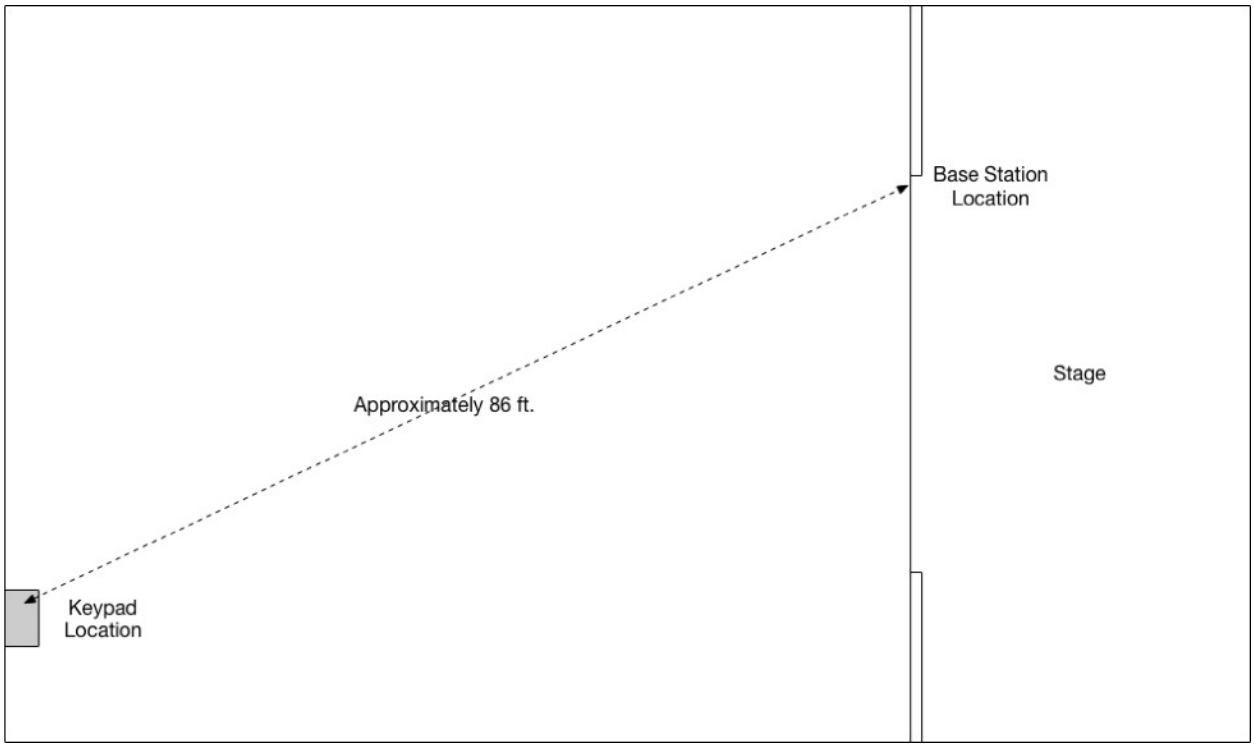
Figure 6: Grafton High School Auditorium for Town Meeting



3.2.2 Municipal Center Gym: Sessions 1-3

While the logistics of performing extensive testing in the auditorium while school is in session are difficult, the Municipal Center gym is conveniently available for testing during a weekday; thus, much of the testing described here was performed in the gym. The gym is approximately 80 feet long and 65 feet wide, with a stage at one end; the stage opening is approximately 36 feet wide. Placing the base

Figure 7: Municipal Center Gym Testing: Sessions 1-3



stations on the edge of the stage and the keypads on a table at the opposite corner allows testing with approximately 86 feet between keypads and base stations. See Figure 7.

The testing procedure consisted of running the ARS Pro application, activating the diagnostic map so that the keypads would be continuously polled, operating one or more keypads, and observing the keypad's behavior. The expected behavior is one more more flashes of the keypad's green light, followed by (1) the light going dark, indicating success, or (2) a flash of the keypad's red light, indicating failure. (At times, the green light would flash after the red light has flashed, but the presence of the red light indicates failure even then.) In most tests, a group of five or ten keypads was operated simultaneously, with that operation repeated five or ten times.

The first four test sessions in the gym yielded largely inconsistent results, with failure rates generally much higher than expected. Analysis determined that laptop's USB configuration was adversely affecting the ability to successfully record keypresses. Consequently, those test results do not contribute to the investigation and are not included in this report. The USB configuration issue was peculiar to the particular laptop configuration used for testing (a Windows 10 virtual machine on an Apple MacBook Pro laptop) and thus not an issue that would affect the normal use of the system on a Windows laptop. After resolving this issue, subsequent testing yielded performance consistent with expectations.

Three more test sessions were held in the gym, testing six combinations of base station channel and separation between base stations:

- Channel 1 assigned to the 970 and to the 971 (with Channel 8 assigned to the other base station, obviously)
- Base stations separated by six feet, three feet, and six inches
- In most cases, operating five Channel 1 keypads and five Channel 8 keypads simultaneously

Table 5: Gym Session 1 Test Results

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Totals
Channel 1 base station	970	970	970	970	971	971	
Channel 8 base station	971	971	971	971	970	970	
# of Channel 1 keypads	5		5	10	10	10	
# of Channel 8 keypads		5	5				
# of test repetitions	10	5	10	10	10	10	
Base station separation	8”	8”	3’	3’	3’	18”	
Channel 1 failures	0		0	0	0	0	0
Channel 8 failures		3	0				3
970 failures	0	0	0	0	0	0	0
971 failures	0	3	0	0	0	0	3

Table 6: Gym Session 2 Test Results

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Totals
Channel 1 base station	970	971	971	970	970	971	
Channel 8 base station	971	970	970	971	971	970	
Base station separation	6’	6’	3’	3’	8”	8”	
Channel 1 failures	0	1	1	1	1	1	5
Channel 8 failures	0	0	0	0	0	0	0
970 failures	0	0	0	1	1	0	2
971 failures	0	1	1	0	0	1	3

Table 7: Gym Session 3 Test Results

	Test 1	Test 2	Test 3	Test 4	Totals
Channel 1 base station	970	971	971	970	
Channel 8 base station	971	970	970	971	
Base station separation	6”	6”	3’	3’	
Channel 1 failures	1	28	0	0	29
Channel 8 failures	28	0	0	0	28
970 failures	1	0	0	0	1
971 failures	28	28	0	0	56

Tables 5, 6, and 7 detail the results of these three test sessions. Some notes about these sessions:

- For all sessions, a failure was noted if the keypad flashed its red light.
- For sessions 1 and 2, a failure was not retried.
- For session 3, a failure was retried until it succeeded.
- For one test in session 1, numeric results were not recorded: a test with the base stations less than one foot apart and Channel 1 on the 971 yielded many failures (Channel 8 was not included in that test).
- The results from session 1 suggested that the separation between base stations was significant; thus, sessions 2 and 3 systematically tested different separation distances
- For session 2, the base stations were placed somewhat more toward the middle of the stage than for the other two sessions.
- In session 2, an additional test was performed to compare the performance of Channel 1 keypads with good batteries and weak batteries. In ten repetitions operating five of each, no failures were recorded.

Key observations from these test sessions include:

- When the base stations are separated by 6-8 inches, the keypads communicating with the 971 fail relatively frequently.
- When a failure was retried, it always succeeded on the first retry.
- Regardless of base station separation and channel assignment, failures occur occasionally.
- There was no difference in the performance of keypads with good and weak batteries.

3.2.3 High School Auditorium

The next test session was held in the Grafton High School auditorium, to compare the performance of the system in the room where Town Meetings are held to the performance in the Municipal Center gym. For this session, the base stations were placed on the stage, near the edge of the stage, and the keypads were placed at the opposite corner, on a railing adjacent to the very last (and uppermost) row of seats, as shown in Figure 8. This places the keypads almost as far from the base stations as is possible in a Town Meeting: approximately 97 feet. The base stations were separated by approximately three feet.

The objective of this test session was to answer the following questions:

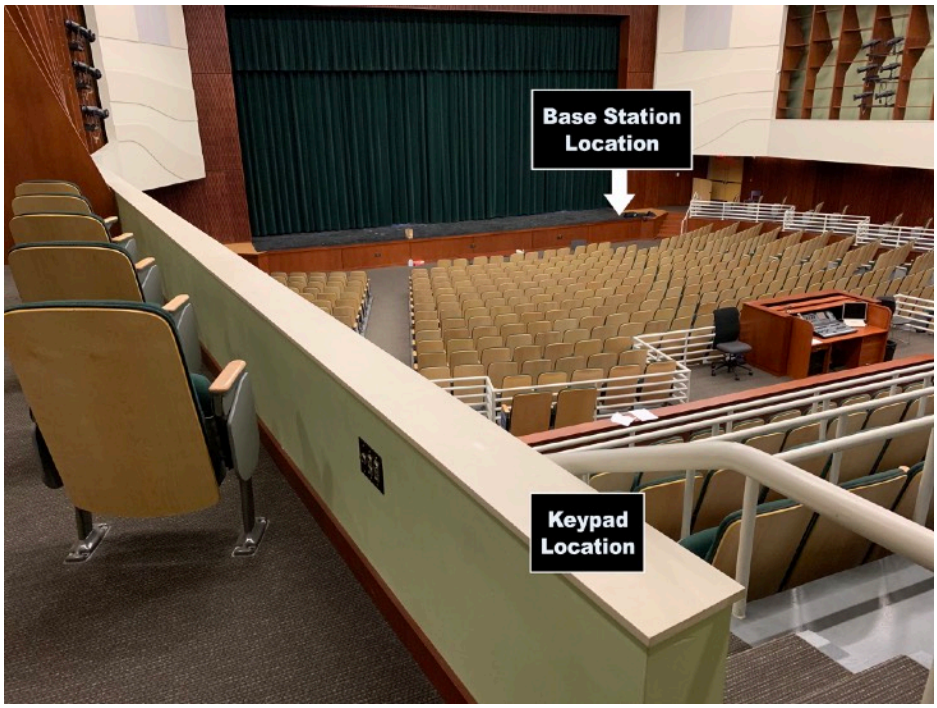
- How well do both channels work together at the maximum distance from the base station?
- How well do keypads with weak batteries work together with keypads with good batteries, at the maximum distance from the base station, for each base station?

The first set of tests in this session operated five Channel 1 keypads and five Channel 8 keypads together, with the two assignments of channels to base stations, and with the Channel 1 keypads having batteries that report good status and weak status. As with previous testing, the ten keypads are operated simultaneously, and repeated ten times for each combination.

Table 8 summarizes the results. Key observations are:

- In all cases, when a keypad failed, it was retried and the retry was always successful.

Figure 8: Auditorium Test Device Locations



- Failures were relatively rare: 1-2% of the time.
- Failures were more or less evenly distributed between the two base stations.
- Weak batteries did not fail more often than good batteries.

The second set of tests in this session compared the performance of Channel 1 keypads with good batteries and with weak batteries, using each base station in turn. Ten keypads were used, operating them simultaneously, repeating each combination ten times. (No Channel 8 keypads were used in this test.)

Table 9 summarizes the results. Key observations are:

- In all cases, when a keypad failed, it was retried.
- With the 970 base station, the failure rate was similar to that obtained in the previous set of tests, and a retry was always successful.
- With the 971 the base station, the failure rate was much worse, and it took as many as four tries before success.

Table 8: Auditorium Session 1 Test Results with 5 Channel 1 and 5 Channel 8

	Test 1	Test 2	Test 3	Test 4	Totals
Base station separation	3’	3’	3’	3’	
Channel 1 base station	970	971	971	970	
Channel 1 battery status	OK	OK	Weak	Weak	
Channel 8 base station	971	970	970	971	
Channel 8 battery status	Fresh	Fresh	Fresh	Fresh	
Channel 1 failures	0	1	0	0	
Channel 8 failures	0	0	2	2	
970 failures	0	0	2	0	2
971 failures	0	1	0	2	3
Good battery failures	0	1	2	2	5
Weak battery failures	0	0	0	0	0

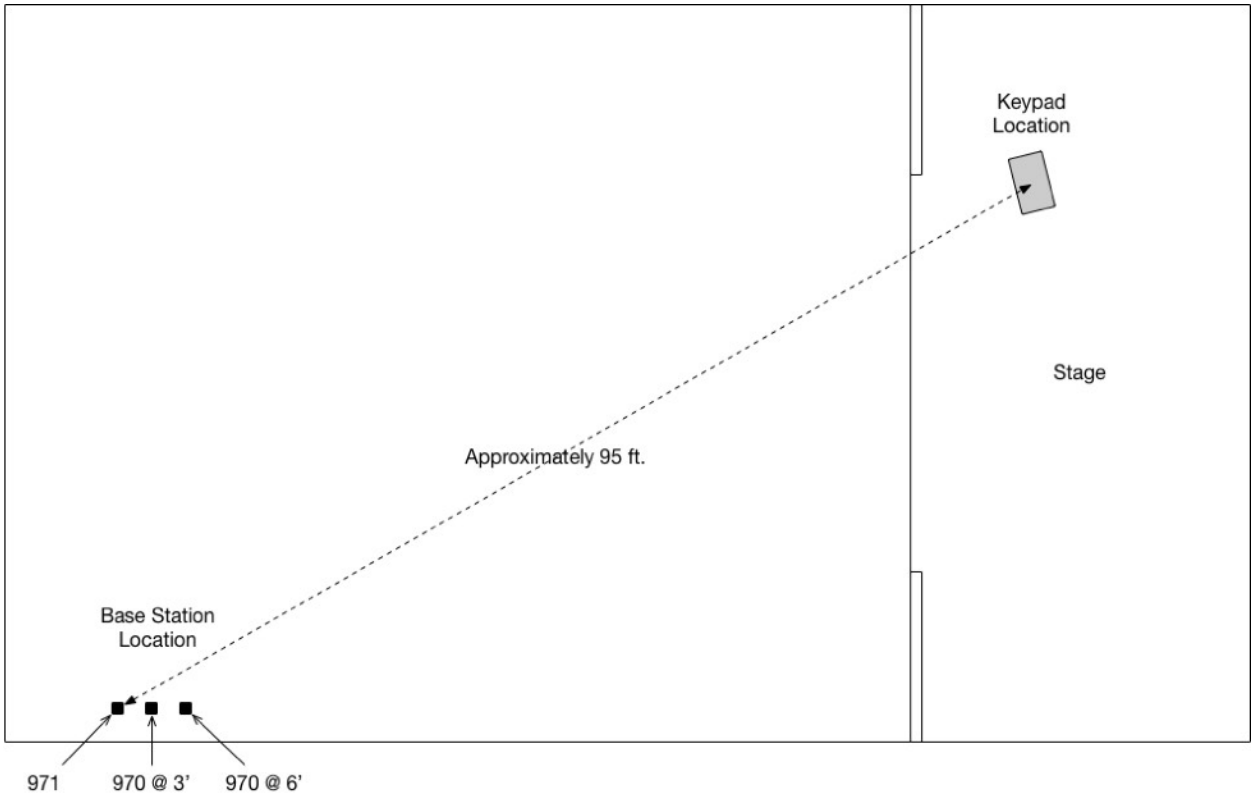
Table 9: Auditorium Session 1 Test Results with 10 Channel 1 Keypads

	Test 5		Test 6	
Base station separation	3’		3’	
Base station	970		971	
Battery status	OK	Weak	OK	Weak
Number of keypads	5	5	5	5
Number of test iterations	10	10	10	10
Failures on first try	2	0	5	8
Failures on second try	0		1	6
Failures on third try				1
% failures on first try	4%	0%	10%	16%
% failures on second try	0%		20%	75%
% failures on third try				17%
Total failures on first try	2		13	
% total failures on first try	2%		13%	

3.2.4 Municipal Center Gym: Session 4

The next test session was held in the Municipal Center gym, with an arrangement that was approximately the same as the arrangement in the auditorium (see Figure 9). The purpose of this test was (1) to replicate the results obtained in the auditorium for the test comparing the performance of good and weak batteries on Channel 1 (tests 5 and 6), and (2) to determine whether increasing the base station separation would reduce the rate of failure in the one scenario that encountered significant failures. Table 10 summarizes the results.

Figure 9: Municipal Center Gym Session 4



The key observations for this test were:

- The results of tests 5 and 6 were indeed replicated, with a similar failure rate when Channel 1 was on the 971.
- Increasing the base station separation to six feet did indeed greatly reduce the failure rate.
- Even with the reduced failure rate, weak batteries failed significantly more than good batteries.

Table 10: Municipal Center Gym Session 4 Results

	Test 1		Test 2		Test 3		Test 4	
Base station separation	Three feet				Six feet			
Base station	970		971		970		971	
Battery status	OK	Weak	OK	Weak	OK	Weak	OK	Weak
Number of keypads	5	5	5	5	5	5	5	5
Number of test iterations	10	10	10	10	10	10	10	10
Failures on first try	0	1	3	17	0	0	3	8
Failures on second try	0	0	2	6	0	0	0	0
Failures on third try	0	0	0	3	0	0	0	0
% failures on first try	0%	2%	6%	34%	0%	0%	6%	16%
% failures on second try			67%	35%				
% failures on third try				50%				
Total failures on first try	1		20		0		11	
% total failures on first try	1%		20%		0%		11%	

4. Conclusions

4.1 Test Results

The conclusions that can be drawn from the testing are the following:

- Separation between base stations affects performance: if they are placed too close together, the keypads associated with the 971 experience significant failures.
- The failures are asymmetric: the 970's stronger radio signal appears to interfere with the operation of the 971, while the 971's weaker radio signal does not observably interfere with the operation of the 970.
- Weak keypad batteries affect performance, although only in marginal situations when attempting to communicate with the 971.

4.2 Consistency with Vendor Information

From the vendor's literature and communication with the vendor, we see that our test findings are consistent with the vendor's information relative to base station placement.

The vendor's user manuals for the WRS970 and WRS971 base stations make the recommendations shown in Figure 10 for base station placement, but note that this does not address the placement of two base stations relative to one another. However, in the troubleshooting section of those manuals we find the advice shown in Figure 11; note the highlighted item about base station separation.

Figure 10: User Manual Advice About Placement

3.2 Placement of the Reply® System

The Base Station can be located anywhere in the area where the keypads are to be used. The base can operate in a room up to 300' x 300' (100m x 100m) in size. The total range of the system is determined by the base and keypad, whichever is shorter. Despite a robust communication system, walls and some other 2.4 GHz devices can moderately to severely limit the WRS971 system's performance. If coverage of a larger area is necessary, elevation of the Base Station or centering in room can usually improve the reception of the keypad signals.

Figure 11: User Manual Troubleshooting Advice

ISSUE	POSSIBLE CAUSE	SOLUTION
Poor RF Performance	Base not in open area.	Do not place the base inside cabinets.
	Base located too close to other electronic equipment	Place the base away from other electronic devices, such as TV's, DVD/VCR players and similar.
	More than one base unit on the same Base ID	Check that the bases covering an area are not on the same Base ID.
	WiFi RF Interference	Verify the WiFi avoidance settings are set correctly in the software. See your network administrator for channel settings.
	Other Interference	Always physically separate other radio devices by at least 10' (3 m). This includes WiFi, Bluetooth, ZigBee and other similar devices.
	Multiple Base Stations are too close	Keep base stations separated and do not stack units.

In various correspondence with the vendor subsequent to the October 2018 Town Meeting, we received the following:

- "Make sure you are set up in an area that you can get the best coverage and that you don't have the base(s) right beside one another and elevated if you can."
- "I know you said in the one test you had the base stations about 3 feet apart. That is definitely something else to keep in mind. You want the bases to be at least that minimum in order for the transmitted signal in one base, will not overwhelm the receive signal in another base."

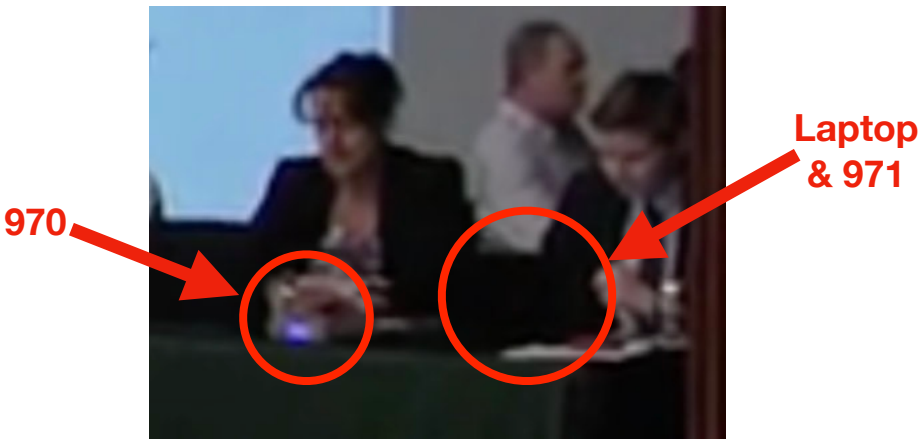
It can be seen that while the vendor's literature does not emphasize the importance of keeping base stations separated, the vendor does state that inadequate base station separation can cause problems, and recommends that base stations be separated by at least three feet.

4.3 Application to Town Meeting

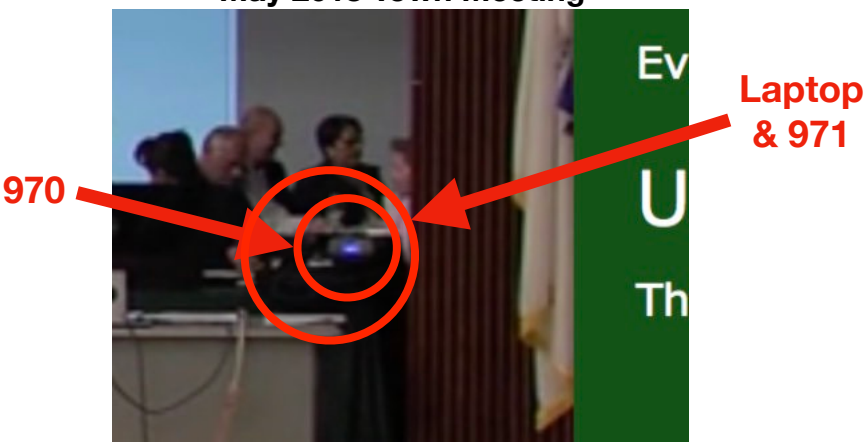
Given the finding that inadequate base station separation can reliably induce failures when keypads are operated at distances comparable to those used at Town Meeting, we reviewed the placement of the base stations at the three meetings where the expanded system was used. Thanks to the Grafton Community Television Video On Demand service, video recordings of the three 2018 Town Meetings

were available for review, and fortunately the video captured the placement of the keypad system base stations. Here, we zoom in on the laptop and base stations in images taken from the video.
While the 971 is not visible in these images, it is known that the 971 was immediately adjacent to the laptop, because it was plugged into a USB hub that was directly plugged into the laptop. It can be seen in these images that the 970 was significantly closer to the laptop and the 971 in May and October than it was in February. This is consistent with the observed behavior of the system in those meetings, with 90% of the checked-in voters having votes recorded in February, compared with 63% in May and 38% in October.

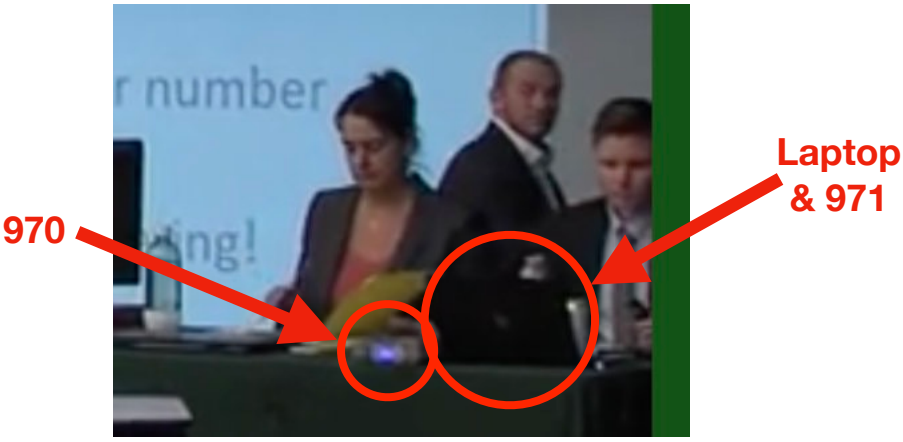
February 2018 Town Meeting



May 2018 Town Meeting



October 2018 Town Meeting



It is also interesting to observe that in the October meeting, 131 of the 142 keypads used in that meeting were Channel 1 keypads, communicating with the 971 base station. We have no record of which keypads were used in the February and May meetings, although it is highly likely that a majority of the keypads used in those meetings were Channel 1 keypads, since approximately three-quarters of the available keypads are Channel 1 keypads. This again is consistent with our testing results, which show that when the two base stations are placed too close together, it is the 971 whose keypads suffer failures.

The battery condition of the Channel 1 keypads may also have contributed to the poor performance, perhaps more so in the October meeting than in the May meeting, as the batteries had aged further at that point. Our testing has shown that when the base stations are sufficiently close together to induce failures, the keypads with weak batteries are more likely to fail than the keypads with good batteries. While weak batteries have not been shown to produce failures when the base stations are adequately separated, they are likely to have added to the failures in this situation.

What may we thus conclude from this analysis?

- The primary cause of the May and October 2018 failures was inadequate separation between the two base stations.
- The assignment of Channel 1 to the 971 exacerbated the failures, because the majority of the keypads were attempting to communicate with the 971 and many were failing due to interference from the 970.
- Aging batteries were not the cause of the failures, but are likely to have increased the number of keypads that failed.

4.4 Other Possible Causes of Poor Performance

Although the test results have quite clearly identified a primary cause for the poor performance experienced at the May and October 2018 Town Meetings, there are a number of other factors that might cause or contribute to poor performance. We note them here, and discuss their relevance to the poor performance we observed.

WiFi interference

Because the system operates in the 2.4 GHz band that is also used by WiFi, it is possible that the presence of very active WiFi use in the auditorium could interfere with reliable operation of the system. We consider it highly unlikely that our use of the system is adversely impacted by WiFi usage, however. While Town Meeting attendee use of WiFi devices may have increased over the three years we have been using the system, the fact that the system performed well in February 2018 but poorly later in the year, with similar attendance at all three meetings, suggests that there were no significant changes in the WiFi environment that could explain the poor performance.

It is also worth noting that should it be determined in the future that WiFi interference may be an issue, the base stations can be configured to avoid the WiFi channel with the strongest or most active signal in the auditorium.

Base station configuration	While it is possible that a misconfiguration of one or both base stations could explain the poor performance, our inspection of the base station configuration did not identify any potential configuration-related problems, and the base station configuration had not been changed between the February 2018 and May/October 2018 meetings.
Base station range	While it is possible that a meeting room may simply be too large for the base stations to cover successfully, we note that even the smaller base station is advertised to cover a room 300 feet square, while our auditorium is approximately 80 feet square — well within the coverage range of both base stations.
Base station elevation	The vendor suggests placing base stations at an elevation relative to the audience; this can be particularly important when the room is flat, to ensure that there is an unobstructed line of sight between the base stations and all keypads. The placement we have been using at Town Meeting achieves this objective: the base stations are on a table on the stage, with an elevation of 6-8 feet above the main floor, and the seating slopes upward from front to rear, assuring an unobstructed line of sight for all keypads.
Structural elements blocking radio signals	Structural elements, such as walls or pillars, can attenuate the radio signal, sometimes sufficiently to cause poor performance. There are no such problematic structural elements in the auditorium.
USB hub	The vendor suggests using a powered USB hub, to ensure that the base stations have a power supply sufficient to transmit at the maximum power of which they are capable. We have been using an unpowered hub, successfully at the February 2018 meeting and successfully during the testing described herein (failures during testing were clearly attributable to base station separation, not to lack of USB power). Nevertheless, it is probably wise to use a powered hub in the future.

4.5 Battery Age

It should be noted that throughout this investigation, it has been assumed that the keypad batteries were new when the Town received the keypads. While replacing batteries, it was observed that the circuit boards in the keypads carried a notation — "4-13" — that appeared to be a date. Consultation with the vendor confirmed that this was likely the date that the boards were manufactured, but that batteries were not inserted into the keypads prior to the time the keypads were made ready for shipment from the factory. This confirms that the keypad batteries were new or nearly new when the Town received them.

5. Recommendations

We recommend the following to ensure reliable performance at future Town Meetings:

- Place the base stations six feet apart.
- Place base stations so that there are no obstacles between them and the audience.
- Configure the WRS970 to Channel 1 and the WRS971 to Channel 8.
- Use a powered USB hub.

- Replace keypad batteries every two years.
- Clearly instruct Town Meeting voters to pay attention to the light on the keypad, to retry the vote if a red light flashes, and to request a replacement keypad if the red light flashes again.
- To test the system at the beginning of Town Meeting, collect the count of checked-in voters from the PollPads, instruct voters to press a button (doesn't matter which one), and verify that the vote count is close to the number of checked-in voters (expect a difference of maybe ten or so, due to voters that check in but do not get keypads, are out of the room at the time, or are not paying attention).