Measurements of the Wireless Ad Hoc Array Concept in a Large Building Setting for Public-Safety Communications

William F. Young, Sandia National Laboratories, Christopher L. Holloway*, The National Institute of Standards and Technology (NIST), Galen Koeppke, NIST, Helge Fielitz, NIST, David W. Matolak, Ohio University

Abstract
Here we report on measurements of the ad hoc array concept in an enclosed atrium/lobby area of a high-rise building in Denver, Colorado. A typical ad hoc network is limited to coverage area achieved by the useable coverage of single nodes; however, we seek to expand the radio frequency coverage by using two or more nodes as elements of an ad hoc array. Previous simulations and theoretical analysis suggest the benefits of the array concept; these measurements in a real-world environment demonstrate that the ad hoc array can provide meaningful gain, up to 10 dB with only four elements. The measurements also indicate a gain of 4 dB to 6 dB using only two elements.

1. Introduction

When emergency responders enter large structures (apartment and office buildings, sports stadiums, stores, malls, hotels, convention centers, warehouses, etc.) radio communication to individuals on the outside is often impaired. Mobile-radio and cellphone signal strength is reduced due to attenuation caused by propagation through the building materials and scattering by the building structural member [1, 2, 3]. In addition, a large amount of signal variability may be encountered due to multipath reflections throughout the structures, which can cause severe signal degradation in communication systems. Here, we report some experimental results on the concept of a wireless ad hoc array to help mitigate the communications problems faced by public-safety personnel (firefighters, police and emergency medical personnel) in disaster situations involving large building structures. The project was sponsored by the Department of Justice Community Oriented Policing Services (COPS) program. This project focuses on two frequencies, 750 MHz and 2.4 GHz. The 750 MHz band is currently of interest because the FCC is in the process of allocating spectrum between 764 MHz and 776 MHz for a nationwide, next-generation interoperable broadband network for use by the public safety community. Results presented here are for the 2.4 GHz band Industrial, Scientific, and Medical (ISM) band.

2. Signal Optimization and Measurement Methods

The idea of using randomly located wireless devices in an intelligent and coordinated fashion for emergency responders was initially investigated in [4, 5]. These initial efforts started with a representation of the optimization problem as infinitesimal dipoles in the presence of several boundary configurations, and used simulation studies to investigate the potential gain available. This report covers the next step in the proof-of-concept process, where the testing is extended to real-world settings.

In the complete optimization, both the power level and the relative phases between the wireless elements are controlled. However, as both the simulation and previous laboratory experiments demonstrate, adjusting of the phase alone accounts for much of
the benefit. Thus, here we use a co-phasing approach [6], where the individual phases of the ad hoc array transmitting elements are adjusted so as to add in-phase at the receiving location. When the ad hoc array is operating in a receiving mode, the collected signal from the array elements are co-phased before addition. In the context of communication system terminology, the case of a transmit array sending to a single receiver is a multiple-input/single-output (MISO) system, whereas the case of a single transmitter sending to multiple receivers is a single-input/multiple-output (SIMO) system. Note however that either the single receiver in the MISO case or the single transmitter in the SIMO case is located within the volume of the array.

A sketch of the experimental setup of the MISO system is shown in Figure 1. This setup was comprised of a transmitting signal generator that fed radiating antenna elements of the ad hoc array. A 1:8 power divider split the power evenly across the array elements, and mechanical phase shifters allowed adjusting of the phase over 360° at 2.4 GHz. The relays and selector switches allowed connection of the phase shifter output into either an antenna element via a 36.6 m RF cable or termination in a 50 Ω load. (The cable loss was approximately 20 dB.) Monopoles mounted on aluminum octagon ground planes with an approximate center-to-vertex measurement of 0.24 m were used for the 2.4 GHz antennas. The ground planes were supported by 1.9 cm (3/4 inch) diameter PVC (polyvinyl chloride) stands at a height of approximately 1.3 m.

![Figure 1. Sketch of experimental setup.](image-url)

The performance of the ad hoc array is measured by placing a receiving antenna within the volume of the array. The receiving antenna, identical to the transmitting array element antennas, was connected to a spectrum analyzer via an 18.3 m RF cable, and the measurement value was obtained by reading the value displayed on the spectrum analyzer. Depending on how rapidly the channel changed and the level of the received signal above the noise floor, the waveform displayed on the analyzer exhibited variable rates of fluctuation. Since the intent of these experiments is not to obtain a precise measurement of the signal power, but rather to quantify the amount of gain possible by
applying the ad hoc concept, the precision of visual observation and recording of the power spectrum was deemed adequate.

3. The Denver, CO Experimental Set-up

The structural construction materials of the Denver building are a typical high-rise combination of concrete and steel, and the lobby area consist primarily of stone, glass, and metal frames. The layout of the ad hoc array elements and the test locations are shown in Figure 2. Two key features of this layout are: 1) the placement of the three array elements, A, B, and C, on the sidewalk outside of the atrium area along 17th Street, and 2) the location of test point 1 outside the main entrance of the atrium.

![Figure 2. Layout of ad hoc array elements and test locations for the Denver site experiments.](image)

4. Discussion of Measurement Results

Figure 3 shows the application of the co-phasing algorithm to the 2.4 GHz case. Figure 3(a) shows results from the co-phasing process, normalized by the strongest contributing element to demonstrate the relative increase. Seven transmitting elements were used for five of the test locations, and six transmitting elements were used for the remaining two test locations (test locations 3 and 7). In the case of test location 3, array element G was not included due to the close proximity to avoid dominating overall performance by a single element (G). At test location 7, array element D was not included for the same reason.

The 6 dB increase is at the theoretical upper bound for two elements, assuming identical gain patterns from the antennas at the test location. For test locations 4 and 6 the gain from two elements is 6.3 dB and 6.1 dB, respectively, which would appear to be a violation of the theoretical maximum. Neither the slow time-varying nature of the environment nor the exactness of the measurement process is taken into account. These factors could readily account for additional 0.3 dB (an approximate 7% error).
Figure 3. Denver measurement results (a) cumulative sum of co-phased power, normalized by the largest contributing element; (b) raw results for co-phase combing of two of the weaker elements; (c) increase over the strongest of the weak signal pair.

Figure 3(a) also indicates that the gain increase from one to four elements ranges between 5.5 and 10 dB. The increase of four to six or seven elements only provides about a 1 dB improvement. (Note that the theoretical free space upper limit is 12 dB and 16.9 dB for four and seven elements respectively.) The variability in received signal level is on the order of tens of decibels while the expected combined systematic and random errors introduced by our measurement equipment are expected to be on the order of tenths of decibels. A key aspect of the array concept is the ability to increase a weak signal to a level that supports communication. Figures 3(b) and (c) are the results using two of the weakly contributing elements. Receive test position 4 shows better than expected gain that is likely due to the test position being in a multipath null condition, where any slight change in the physical environment (e.g., array element movement due to wind, a door opens, etc.) could cause the depth of the null to vary significantly. The 15 dB improvement would thus represent a combination of the benefit due to source co-phasing and a decrease of the null depth. More importantly, at least 1 dB of gain was realized, and in most cases, more than 2 dB was possible when co-phasing two relatively weak signals.


