

Mississippi Transportation Research Center

Implementation of a Real-Time Intersection Accident Detection System (Phase 1)

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Prepared by:

Yunlong Zhang
Department of Civil Engineering
Mississippi State University

Rose Qingyang Hu
Department of Electrical and Computer Engineering
Mississippi State University

Yuanchang Xie
Department of Civil Engineering
Mississippi State University

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Navaneethakrishnan Balraj	Department of Electrical and Computer Engineering
Sumit Arora	Department of Electrical and Computer Engineering

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ABSTRACT

The focus of this research is the feasibility study for the implementation of a real-time accident detection system at intersections. After reviewing accident detection algorithms investigated in the prior phase of this research, we explored schemes to improve the detection algorithm, conducted algorithm tests both in the lab and in the field, investigated system architecture and communications designs, and evaluated the feasibility of system implementation.

Based on the original optimal algorithm with Discrete Wavelet Transform (DWT) feature extraction method identified from the previous project, two algorithm refinement schemes, a lifting scheme and an overlapping scheme, were investigated. Lab and field test results consistently show that the overlapping scheme has a higher detection rate than the original optimal algorithm, and the lifting scheme has the advantage only in computation time.

The feasibility of system implementation was investigated from several perspectives including detection rate, computation time of the algorithm, and communications design. Based on the results of the study, a real-time system implementation scheme was recommended.

CHAPTER 1. SUMMARY OF ALGORITHMS INVESTIGATED

1.1 Introduction

The automated accident detection algorithm can largely be categorized into two groups. The algorithms in the first group are directly based on accident features such as sound and image, and those in the second group are based on the symptoms of the accidents, such as changes in traffic volume, speed, and occupancy.

Because the relationship between accident and traffic flow characteristics is not always explicit, it is very hard to define which traffic parameter values and patterns are representative of normal traffic and which are representative of an accident. This is true especially on surface streets. Moreover, a lot of issues such as time-of-the-day, weather, signal timing and locations can change the parameter values, and as a result, a simple traffic jam during morning peak hour could also be classified as an accident by some algorithms based on inferences from traffic parameters. Detection directly based on audio sounds or video images may thus provide some advantages.

Image-processing based accident detection is possible, but it is neither cost effective nor computationally efficient compared with audio-based detection methods [1]. Several researchers have successfully applied wavelet transformation to analyze traffic sound and detect accidents, and the procedure based on wavelet analysis was also adopted as the

base-line method during the algorithm development stage in this accident detection research. Normally, there are three major steps involved in the audio accident detection method based on wavelet analysis. Those three steps are signal collection, signal feature extraction and optimization, and feature classification. This pattern recognition process is illustrated in Figure 1. The following subsections of this chapter will summarize the previous study on those steps.

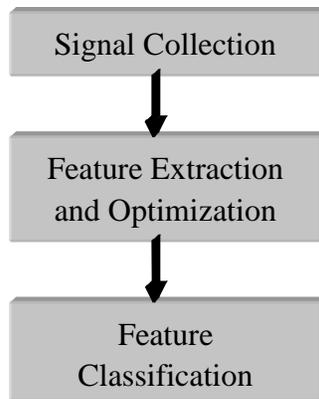


Figure 1 Major steps in audio pattern recognition

1.2 Feature Extraction

In the previous studies [1,2,3], the authors compared five feature extraction methods, which are based on the following transforms:

- Discrete Wavelet Transform (DWT)
- Fast Fourier Transform (FFT)
- Discrete Cosine Transform (DCT)
- Real Cepstral Transform (RCT)

- Mel frequency Cepstral Transform (MCT)

The test results show that compared with other feature extraction methods, extraction based on DWT can provide the highest classification accuracy. DWT was thus adopted as the feature extraction method in this project.

The development of the Discrete Wavelet Transform was motivated by the fact that DWT offers some advantages in analyzing the temporal and spectral properties of non-stationary signals such as traffic acoustic signals. A feature vector, \vec{F} , is formed through computing the root-mean-square (RMS) energy of the wavelet detail coefficients at each scale, ED_j and the RMS energy of the wavelet approximation coefficients at the final scale, EA_M ,

$$\vec{F} = [EA_M \quad ED_M \quad ED_{M-1} \quad \dots \quad ED_1]^T \quad (1-1)$$

Where the superscript T denotes a vector transpose, and

$$EA_M = \frac{1}{P_M^A} \sqrt{\sum_{i=0}^{P_M^A-1} [A_M(i)]^2} \quad (1-2)$$

$$ED_j = \frac{1}{P_j^D} \sqrt{\sum_{i=0}^{P_j^D-1} [D_j(i)]^2} \quad (1-3)$$

For $j = 1, 2, 3, \dots, M$, the constant M is the maximum wavelet decomposition level; P_j^D is the number of detail coefficients at level j ; and P_M^A is the number of approximation coefficients at level M . According to equation (1-1), after the DWT feature extraction, the data space dimension is reduced to $M + 1$. The value of M is determined by the wavelet filter length and the original signal length. The most it can

ever be is $M = \log_2(N)$, where N is the length of the original signal and the mother wavelet's high-pass and low-pass filters have length 2, as in the case with the Haar mother wavelet. However, for longer mother wavelets, such as the higher order Daubechies or Biorthogonal mother wavelets, the maximum scale M can be much lower.

We compared the DWT feature extraction methods based on different mother wavelets such as Haar, Daubechies4, Daubechies15, Coif lets2, Coif lets5, Symlets2, and Symlets8. All the features extracted are optimized and classified, and the classification results show that DWT based on Haar mother wavelet can consistently achieve the best accuracy. In this project, DWT with Haar mother wavelet was adopted. And when we refer to DWT in this report, it means DWT with Haar mother wavelet.

1.3 Feature Optimization Method

The Fisher's Linear Discriminant Analysis (LDA) method is selected for feature optimization. LDA is based on the projection of the whole data set, and it tries to maximize the intraclass variance and minimize the interclass variance. A simple example of LDA is shown in Figures 2 and 3.

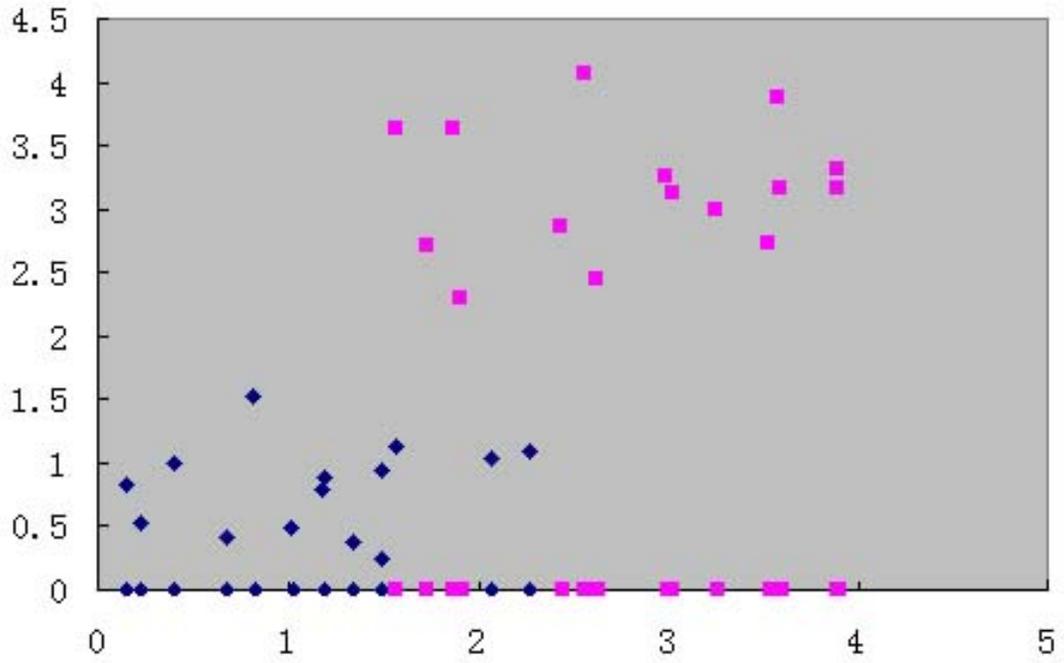


Figure 2 Projection of data onto x-axis

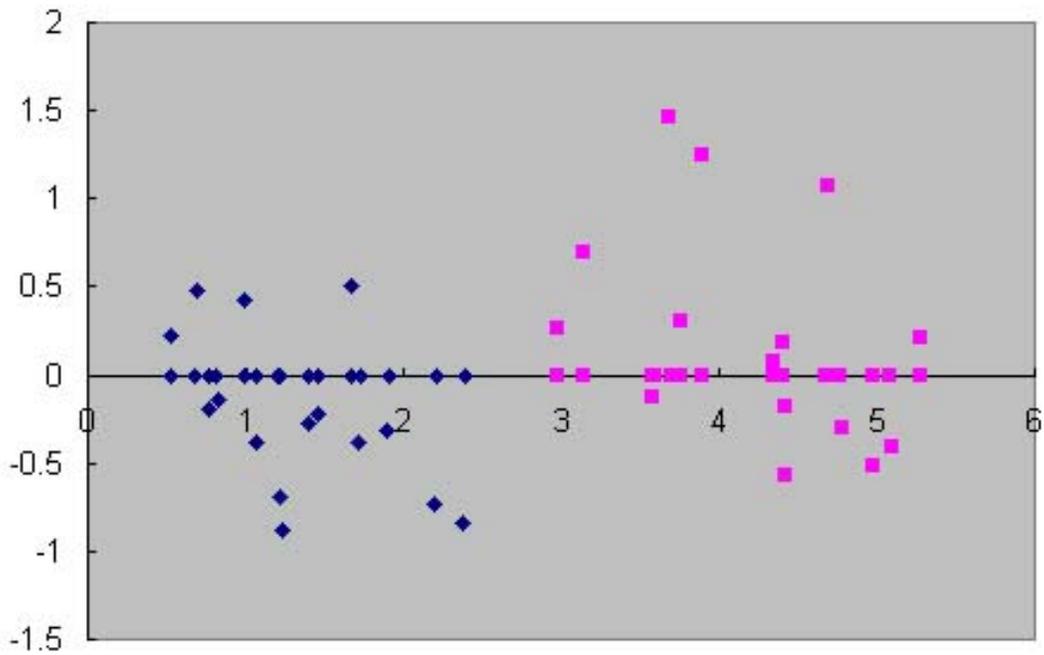


Figure 3 Projection of data onto line $y=x$

If we project the data set onto the x -axis in Figure 2, some of the data from different groups will be mixed up. But if we project the data set onto line $y=x$, the result is in Figure 3, which clearly shows a better separation between the two sets of data. Linear Discriminant Analysis method is to find the optimal projection baseline that can best separate different data sets, and it has been widely applied to pattern recognition, and was chosen for feature optimization in this project.

1.4 Feature Classification Method

Three statistical classification methods were investigated in our previous research, which are nearest mean, nearest neighbor, and maximum likelihood. Many classification tests were conducted and the results of the three classification methods were compared. The results showed that maximum likelihood classification method yielded the highest classification accuracy, and was thus chosen to be the feature classification method.

CHAPTER 2. ALGORITHM REFINEMENTS FOR REAL-TIME IMPLEMENTATION

To facilitate the real-time implementation of an automated accident detection system, a lot of research work was conducted to improve the speed and performance of the detection algorithm. Particularly, we proposed to use a lifting scheme to speed up the algorithm, and also developed an overlapping scheme to improve the classification accuracy. The performances of the refined algorithms were tested in a lab environment in real-time by running the detection programs while playing back recorded sound signals.

2.1 Lifting Scheme [1]

In order to meet the requirement of a real-world system, the detection algorithms must be fast enough for real-time applications. The computational time proved to be faster with the lifting scheme compared with other existing algorithms based on the discrete wavelet transform [4]. The main property of the lifting scheme is that all the derivation is from the spatial domain. This is in contrast to the conventional approach where the derivation is based on the frequency domain. The main advantage of being in the spatial domain is that no prerequisite of Fourier Transform is required. When the system is installed, it will perform at least one feature extraction operation every 3 seconds. If we use the lifting scheme to improve the processing speed of the traditional

DWT-based feature extraction method, it will save a lot of computation time.

2.1.1 Lifting Scheme Algorithm

Following is a brief explanation of the lifting scheme. Let us consider a signal x_n with 2^n samples. This signal needs to be transformed into an approximate signal x_{n-1} and a detail signal d_{n-1} , as in traditional filter tree algorithms. The lifting scheme consists of three steps: split, predict and update. The block diagram of the lifting scheme is shown in Figure 4.

1. **SPLIT:** The input signal is divided into two disjoint sets: x_{2l} with even indexed samples and x_{2l+1} with odd indexed samples. Each set has half as many as the original input signal. This splitting of the signal into even and odd sets is called the *Lazy wavelet transform*.

$$(x_{n,2l}, x_{n,2l+1}) = \mathbf{Split}(x_n) \quad (2-1)$$

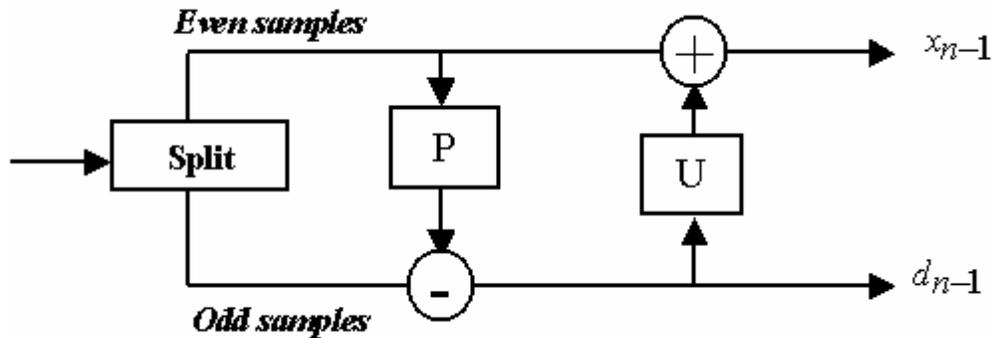


Figure 4 Block diagram showing lifting scheme

2. PREDICT (P): If the signal has a local correlation structure, the even and odd subsets will be highly correlated. That is, with one of the subsets, it should always be possible to predict the other one with a certain level of accuracy. Usually an odd indexed sample $x_{n,2l+1}$ will use its even indexed sample $x_{n,2l}$ as its predictor. The detail $d_{n-1,l}$ is defined as the difference between the odd sample and its prediction.

$$d_{n-1,l} = x_{n,2l+1} - \mathbf{P}(x_{n,2l}) \quad \text{or} \quad d_{n-1} = \text{odd}_{n-1} - P(\text{even}_{n-1}) \quad (2-2)$$

3. UPDATE (U): One of the key properties of the approximate signals is that they have the same average value as the original signal. To ensure that this property is satisfied, the update stage performs the following operation.

$$x_{n-1,l} = x_{n,2l} + d_{n-1,l} / 2 \quad (2-3)$$

Which defines an operator U of the form:

$$x_{n-1} = \text{even}_{n-1} + \mathbf{U}(d_{n-1}) \quad (2-4)$$

The details on the derivation of the above equations can be found in [5]. All three steps of the lifting scheme help to retrieve the required approximate and detail signals from a given signal, thus obtaining the results as in a traditional filter tree approach. A feature vector is obtained by computing root-mean-square (RMS) energy of the detail and the approximate coefficients at each level.

2.1.2 Testing Results and Conclusion

To test the effect of the lifting scheme, we conducted comparisons between different design schemes. First, the authors considered two different types of feature extraction methods: DWT scheme and the lifting scheme. The system is designed such that the audio signals could be either classified using a two-class system (crash or non-crash) or a multi-class system (crash, normal traffic, pile drive, siren, bird chirping, etc.). Maximum likelihood classifier and LDA were used as the methods for feature classification and feature reduction respectively.

Tables 1 and 2 show the maximum likelihood classification results comparisons between the DWT scheme and the lifting scheme. All results reflect the leave-one-out testing scheme: a crash signal or special non-crash (breaking, sirens, etc.) is tested based on the classified database that excludes the signal being tested. Table 1 is for the two-class system, and Table 2 is for the multi-class system. Clearly, both DWT and the lifting schemes provide satisfactory detection results in both two-class and multi-class systems, but the DWT's performance is consistently better. Among all 4 combinations, the two-class system with the DWT method performed the best, achieving 94% overall accuracy with a 95% confidence interval at 0.04. Thus DWT method using the Haar mother wavelet would be a better choice, based on the overall classification accuracy, for implementation of the algorithm in real time system. The lifting scheme, due to its much faster execution, may also be considered in a real-world system where computation time

becomes an issue, such as in a system with many intersections.

Table 1 Maximum likelihood classification accuracies for two-class system

Feature Extraction Method	Crash	Normal	Overall Accuracy	Confidence Interval (95%)
DWT scheme	96.3%	93.8%	94.4%	3.6%
Lifting scheme	85.2%	93.8%	91.7%	4.4%

Table 2 Maximum likelihood classification accuracies for multi-class system

Feature Extraction Method	Crash	Normal	Piledrive/ Brake	Bird chirping/ siren	Overall Accuracy	Confidence Interval (95%)
DWT scheme	92.6%	98.4%	70.0%	77.8%	92.6%	3.5%
Lifting scheme	88.9%	91.9%	0.0%	55.6%	79.6%	6.4%

2.2 Overlapping Scheme

2.2.1 Overlapping Scheme Algorithm

Based on experiments and other researchers' studies, we chose the input signal length to be 3 seconds, which is appropriate for most signals. If the signal length is too long, then one signal may contain the combination of several sounds such as crash, brake, or other incidents, which will make the signal too complicated to analyze. On the other hand, if the signal length is too short, for example, 1 second, one crash or brake sound may often be split into two successive signals. The feature extraction method can not extract a complete feature from either of those two signals, each containing only part of the crash sound, thus a crash may not be correctly detected.

Even with a 3 second signal length, it may still happen that one crash sound is split into two signals even though the probability is smaller compared with the case with a one-second signal length. In addition, it's also common that two or more crash sounds may occur within 3 seconds. To separate these crash sounds correctly is essential for accurate crash detection.

To overcome the two aforementioned problems, we proposed and tested an overlapping scheme, which uses a 3-second window to sample the original input sound every second. This scheme results in an overlapped portion between two consecutive samples and the overlapped signal length is 2 seconds. With this, the instance that one sound splits into two signals can be mostly avoided. For example, since we continuously sample the input sound with a 3-second window every second, the end of the first signal is in the middle of the next signal, and its beginning is in the middle of the previous signal. Even if one crash sound is split into the first signals, it will be completely included within the third signal. The other problem we mentioned before can also be effectively avoided by the overlapping scheme. This is illustrated by Figure 5, which shows one signal that has two crashes occurring within 3 seconds. If we simply use the 3-second window to sample this signal, what we will get probably is the portion indicated by the solid line. But if we use the overlapping scheme and sample the signal every 1 second using a 3-second window, then the chance we can separate the two crashes will be greatly increased, as indicated by the dashed lines in Figure 5. By decomposing the signal with

multiple crashes into several simple signals with a single crash, we can reduce misses of crash detection and improve the overall detection rate.

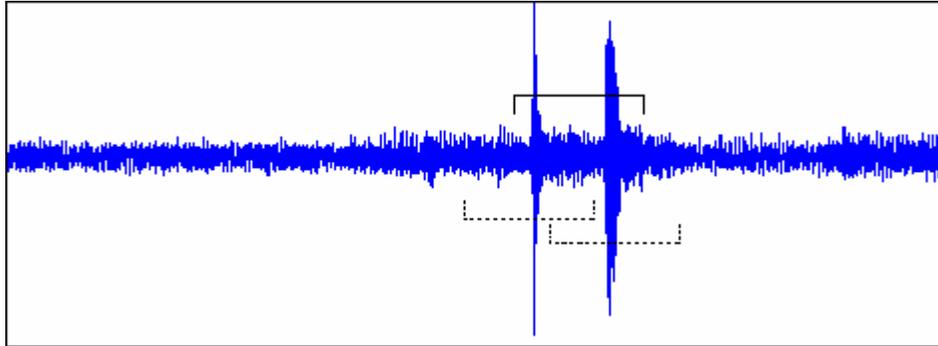


Figure 5 One signal that has two crashes occurred within 3 seconds

The test results of the overlapping scheme also verified that the new method has a very good capability in reducing misses of crashes. Figure 6 shows a 3-second signal that has 2 crashes, and the DWT scheme failed to detect the crashes. Figure 7 shows the decomposition result of the overlapping scheme. Two crash signals were isolated from the signal in Figure 6, and both of them were classified as crashes using the DWT scheme. One thing worth mentioning is that the overlapping scheme only changes the way we sample the input sound, to explore as much useful information as possible. It doesn't influence the feature extraction and classification process.

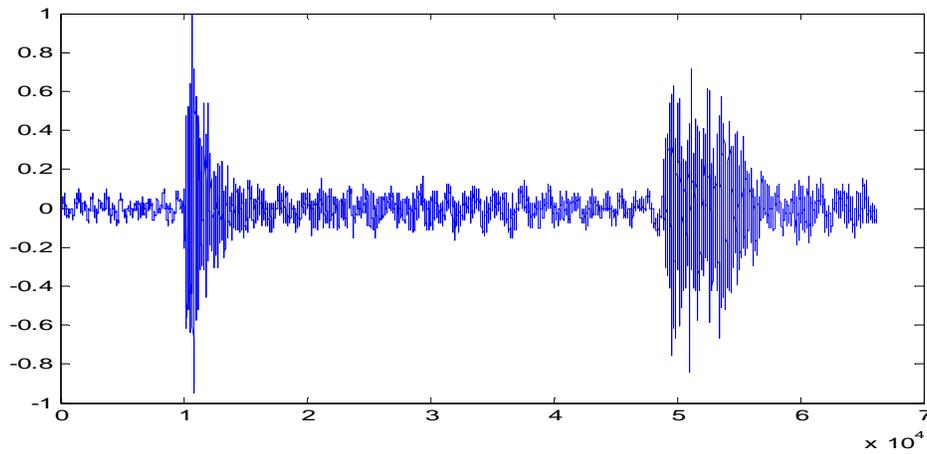


Figure 6 Using 3-second window to sample the input sound

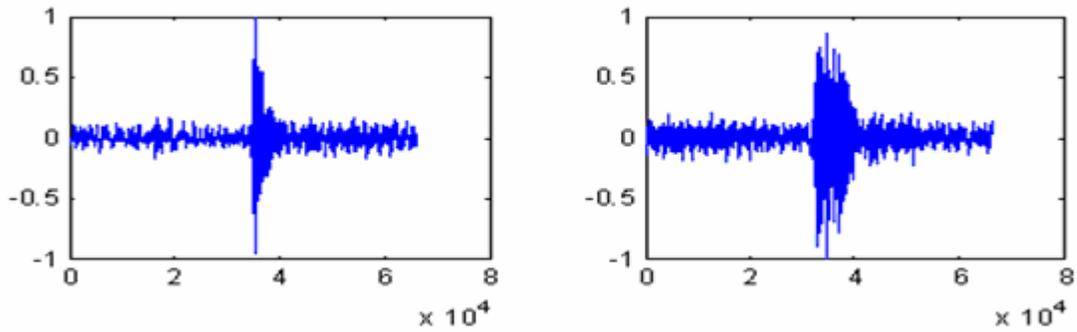


Figure 7 Application of overlapping scheme

2.2.2 Lab Real-Time Testing and Results

To test the effectiveness of the overlapping scheme, we selected 16 crash video clips from the TRIMARC project, which was conducted by the Kentucky Transportation Cabinet, City of Louisville Public Works, Louisville Police Department, Northrop

Grumman, and Mitsubishi Electric Company. These videos include the background and crash sounds, and can best represent the real-time environment. Results without the overlapping scheme (procedure shown in Figure 8) and with the overlapping scheme (Figure 9) were compared and the results were tabulated in Table 3.

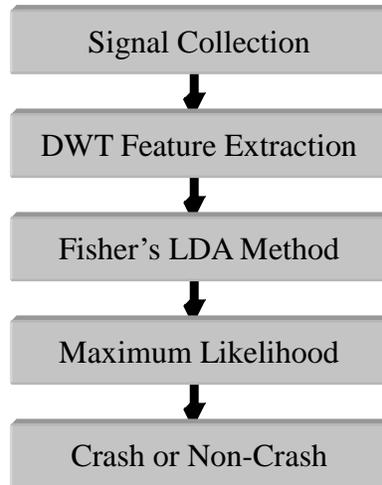


Figure 8 Algorithm based on DWT(Haar) feature extraction

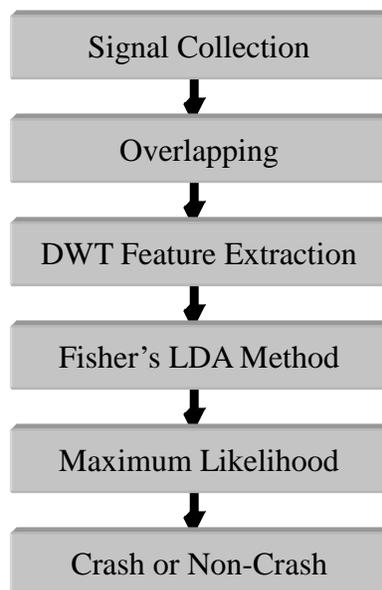


Figure 9 Algorithm based on DWT(Haar) feature extraction and overlapping scheme

Table 3 Result comparison between traditional DWT and overlapping

Signal	# of Crashes	No Overlapping		Overlapping	
		Crash	Miss	Crash	Miss
1	2	1	1	1	1
2	2	2	0	2	0
3	2	1	1	2	0
4	1	1	0	1	0
5	2	2	0	2	0
6	1	1	0	1	0
7	2	1	1	2	0
8	2	2	0	2	0
9	1	1	0	1	0
10	1	1	0	1	0
11	2	2	0	2	0
12	5	5	0	5	0
13	5	4	1	5	0
14	2	2	0	2	0
15	2	2	0	2	0
16	2	2	0	2	0
Total	34	30	4	33	1
Accuracy	----	88.2%		97.1%	

The results show that the overlapping method improved accuracy, especially when there are two or more crashes occurring in one 3-second signal. Having several crashes in three seconds is common, since one accident may have more than one crash sound and sometimes one accident may cause several immediate secondary crashes. A few actual cases with multiple crashes occurring within a short time span are shown in Figures 10, 11 and 12. We can certainly see the need of addressing this issue and the proposed overlapping scheme can do exactly that task.

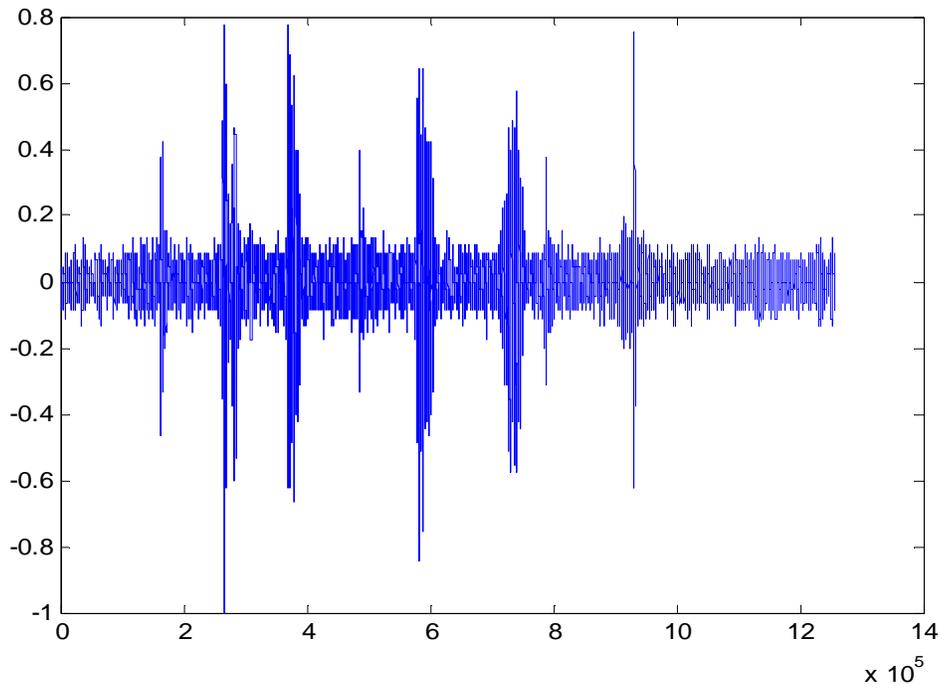


Figure 10 Sample signal 1 with multiple crashes

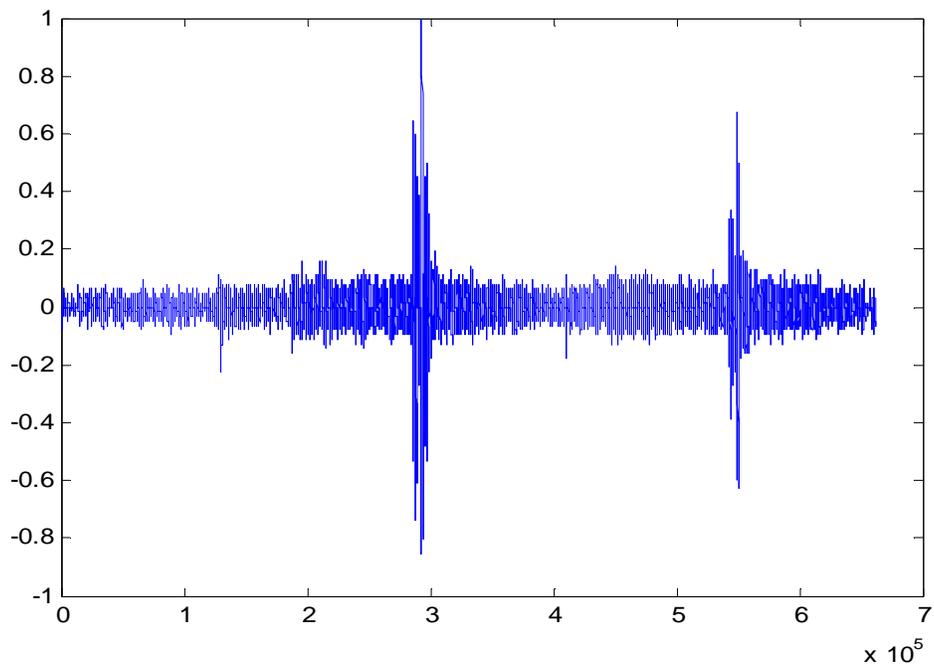


Figure 11 Sample signal 2 with multiple crashes

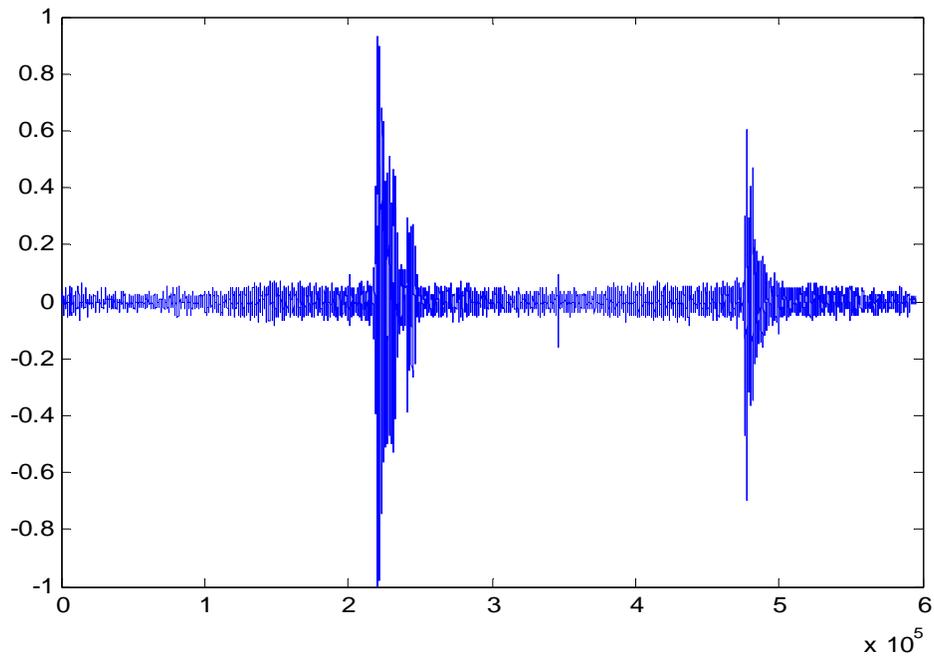


Figure 12 Sample signal 3 with multiple crashes

One important issue that needs to be pointed out is the computation efficiency. Although the overlapping method triples the detection time, the system can still be fast enough to meet the real-time need during the testing using a laptop with the following system configurations:

1. CPU: Mobile AMD Athlon™ XP 2400+ 1.79GHz
2. Memory: 512M
3. Operation System: Microsoft Windows XP Professional 2002
4. Signal Processing Tool: MATLAB 6.5

2.3 Summary of Algorithm Refinements

In this study, we proposed two improvements, a lifting scheme and an overlapping scheme, to the baseline DWT scheme developed in the previous stage of the research. The test results in Tables 1 and 2 show that although the lifting scheme can improve the computational efficiency of the detection algorithm, its detection accuracy is consistently lower than that of the DWT. Faster speed was achieved at the expense of lower accuracy. For an accident detection system, accuracy is the most important factor and speed is secondary as long as real-time processing is still maintained. Because of this we will not recommend using the lifting scheme in our accident detection system as long as adequate computational resources are available to provide real-time applications.

The overlapping scheme uses a 3-second window to sample the input sound every second and avoids two major problems that may cause negative effects on detection rate. Theoretically the overlapping scheme should have higher crash detection accuracy than the DWT scheme or the lifting scheme; this is confirmed by the results in Table 3. Compared with the DWT scheme, an overlapping scheme will triple the detection time, it can make better use of the available input sound and it also significantly improves the crash detection rate. We used a laptop to do real-time data sampling and ran the detection algorithm based on an overlapping scheme, and it didn't show any delay. In real-world implementation, with properly designed system architecture, more powerful computers, and well-written algorithm code, the computational time should not be an

obstacle for adopting the overlapping scheme.

The performance comparisons are summarized in Table 4. Based on the comparisons, the overlapping scheme is recommended for future system implementation due to its high detection rate. However, in a large system or in a system with limited computational capability available, the DWT scheme without overlapping can be used. If speed becomes a real issue, the lifting scheme may also be used for reasonably high detection accuracy.

Table 4 Comparison among original DWT, lifting scheme, and overlapping scheme

	DWT scheme	Lifting scheme	Overlapping scheme
Detection rate	Better	Good	Best
Computation time	Less	Least	Most

CHAPTER 3. REAL-TIME SYSTEM TEST IN THE FIELD

All the tests reported in Chapter 2 are real-time testing. The tests were conducted by playing back recorded audio signals. The results reported in chapter 2 on one hand provide the basis of algorithm selection for real-world systems, and on the other hand, they also present the real-time testing results of the selected algorithm. Results of the lab testing by playing back original audio crash signals recorded at intersections in real time are also reported in [1,2]. In order to achieve more convincing test results, we also conducted field tests at one typical intersection in the downtown area of Starkville, MS.

3.1 Real-Time Testing Using MATLAB Simulink

The real time accident detection processing is developed in MATLAB Simulink. The system uses an external sound card to send the recorded signal to the Simulink. The input signal to the Simulink is a series of three-second frames with 66,176 samples. The testing was either conducted at intersection in real time while audio signals are being collected, or processed in real time while the recorded signals are being played back. Before any processing was conducted, all signals were normalized such that each signal's maximum amplitude was one. For every incoming signal, it was processed by extracting energy features using discrete wavelet transform or a lifting scheme. It was

then compared with the classified database and classified when its feature was similar to any of the signals in the training database. When a signal is identified as “crash”, an alert signal is produced.

Figure 13 shows a block diagram of the real-time testing system using MATLAB Simulink. Figures 14-16 show the windows of the real time system using Simulink in MATLAB. Figure 14 is the actual system that is being used. Figure 15 shows a plot of an incoming signal, and Figure 16 is the final output which is a plot of the signal being labeled as “crash.”

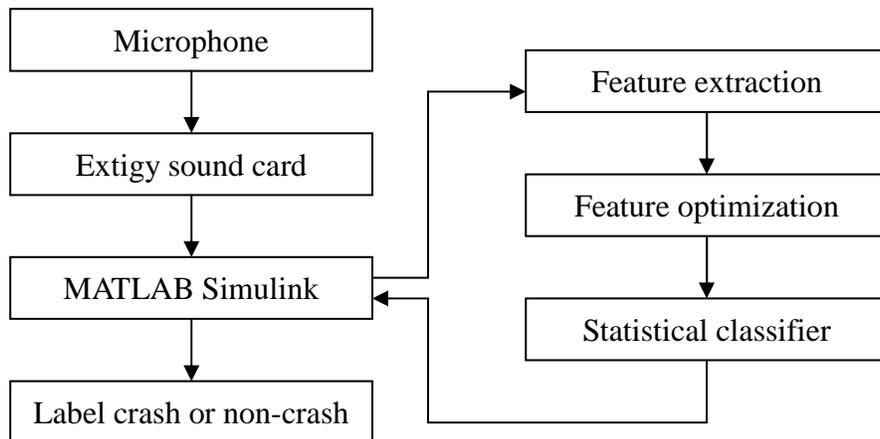


Figure 13 Block diagram of real-time testing system using MATLAB Simulink

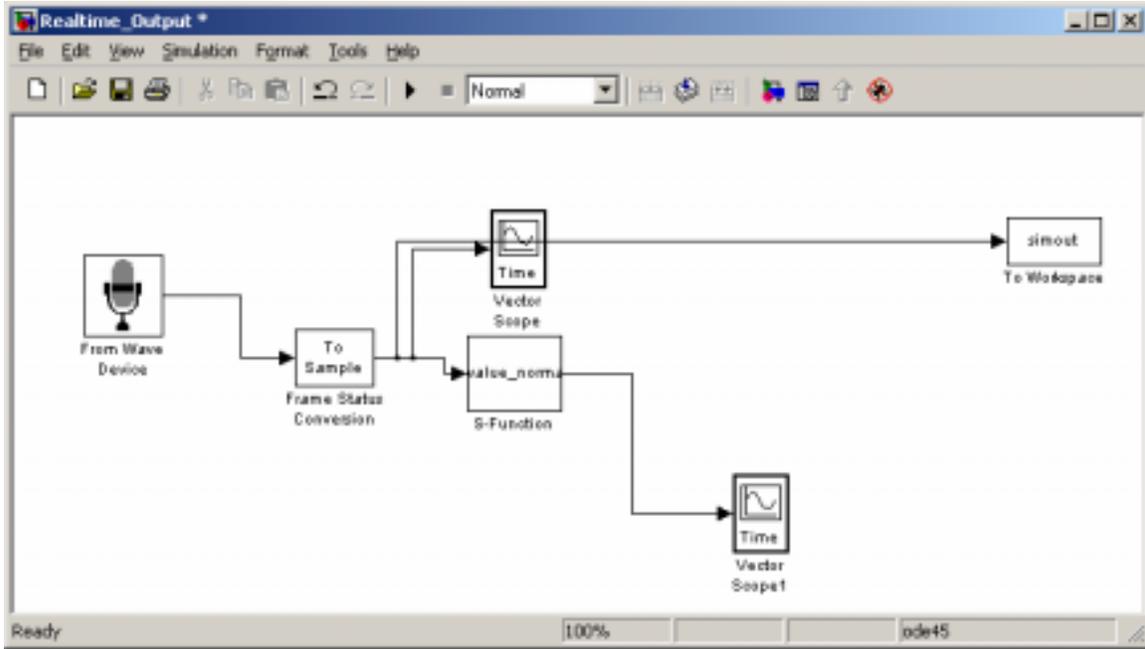


Figure 14 Real-time detection system using MATLAB Simulink

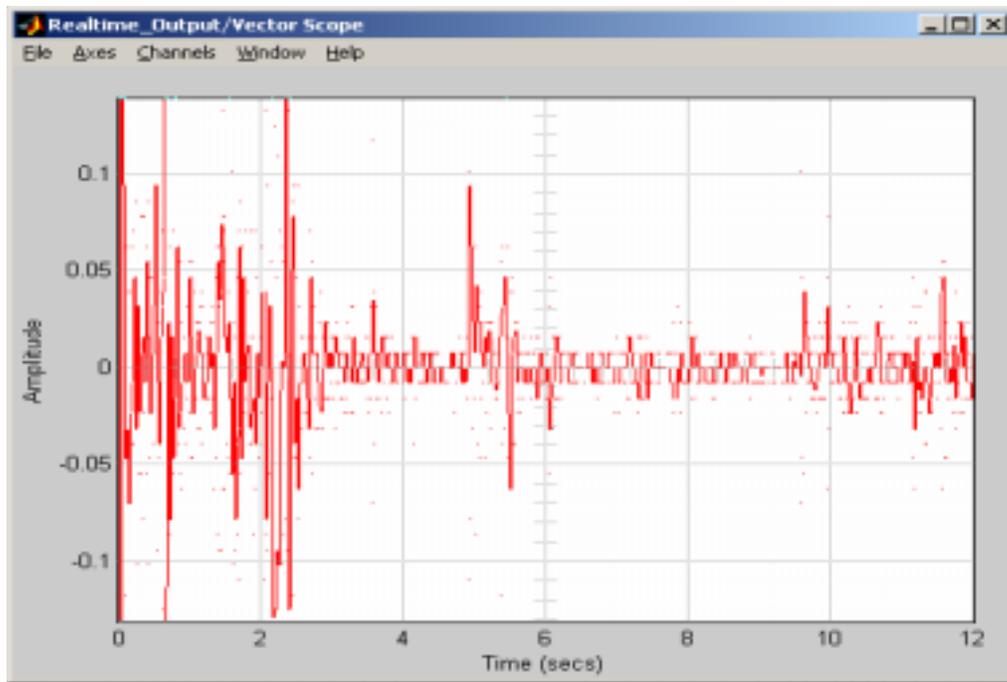


Figure 15 Plot of incoming signal

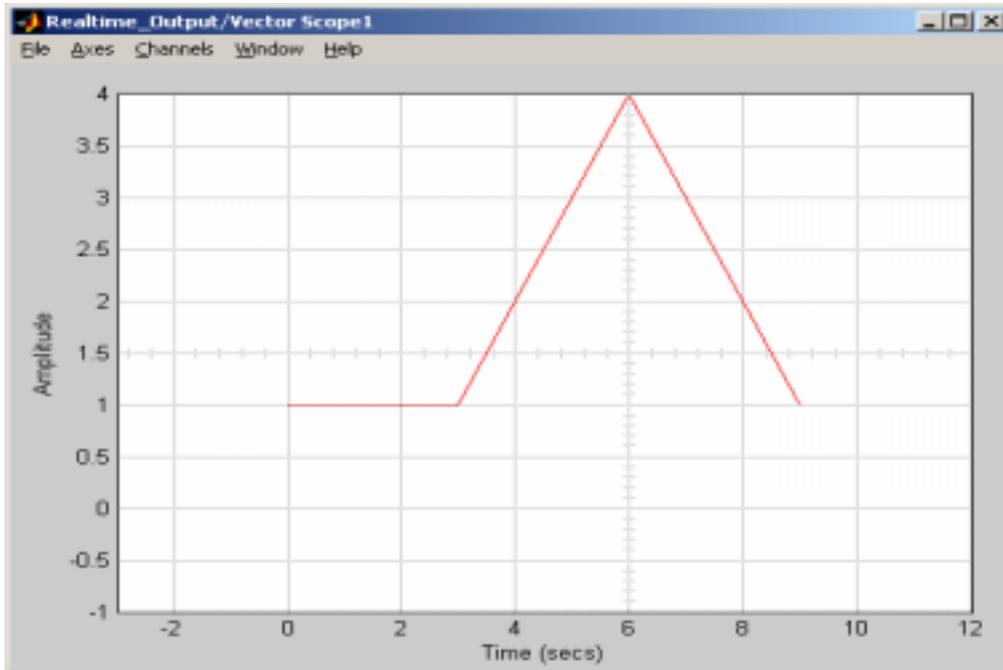


Figure 16 Plot of a signal classified as “crash”

3.2 Test Design

The test was carried out at the intersection of Montgomery and Veterans Memorial Highway, a very busy signalized urban intersection. The traffic consisted of passenger cars, vans, pick-up trucks, and tractor trailers. The test time was between 14:00 pm and 15:00 pm on May 14, 2004.

Since it is too difficult to catch a real accident occurring during the test, we played 34 crash signals at the intersection to mimic the true accident scenario with the actual background sound. These crash signals are identical with the data we used in the lab test of the overlapping scheme. We didn't prepare any normal signals, because the

background traffic at the test site is more appropriate and it is not necessary to find any additional normal signals. Accident detection rates and false alarm rates were compared among the three methods.

3.3 Test Results Analysis

The DWT scheme, the lifting scheme, and overlapping scheme were tested, and the test results are listed in Table 5. For all three methods, during the 1-hour test period there is no normal sound misclassified as crash. So each method has a 0.0% false alarm rate.

Table 5 Field test results

	DWT scheme	Lifting scheme	Overlapping scheme
# of crashes	34	34	34
# of crashes detected	29	23	31
Detection rate	85.3%	67.6%	91.2%

Compared to the lab test results, the accident detection rates in this field test results are relatively low. But the order of detection rates is the same: the overlapping scheme has the highest detection rate and the lifting scheme has the lowest detection rate among the three methods. This shows that the detection performance of our system is consistent. One interesting and desirable thing is that the false alarm rate of field detection is much better compared to that of the lab test result. There may be two reasons for this: first, the normal sounds we used in the lab test are not very typical; second, the field test time is not long enough and some equivocal normal sounds didn't happen during the test.

Comparisons between Tables 1, 2, 3 and 5 also show that the lab test results of detection rate are obviously better than the field test results. There are also two possible reasons for this. First, the accident sounds we played were recorded from real accidents happening at intersections, and they already included the background sound. When we played these accident sounds during the test, the inputs to our detection system were not only the recorded accident sound, but also the pure traffic background sound at that intersection. This combined input sound changed the feature of recorded accident sound, thus reducing the detection rate. Second, when we were doing the real-time field test, the on-vehicle speaker was used to play the accident sound. It is very difficult to adjust the volume of the speaker to an optimal point that can best balance the accident sound against the pure background traffic sound. So sometimes the volume of accident sounds was relatively higher than the background traffic sound, and sometimes the volume of accident sounds was inundated by the background traffic sound. The features we extracted from these input sounds also varied consequently with those changes and may have caused the deterioration of the detection rates.

The crash signals we used in real-world field testing were recorded at intersections and have already included the background sound. While in the lab environment it is very quiet and the recorded sounds, which are the actual sounds as the crashes occurred, can be considered as the only inputs to the detection system. Because of this, we have a reason to believe that the detection results from the lab tests better represent the true

performance of our detection algorithms. Although the detection rates of field test are inferior to the lab test results, it again showed the benefits of using the overlapping scheme since with the overlapping scheme the system was still be able to achieve a 91% detection rate even under adverse conditions. The real performance of detection rate in the field is yet to be defined. Installing the system at intersections with extremely high accident rates may seem to be a solution, but at this stage we do not have the hardware in place to conduct an actual field test of an extended duration.

As expected we were not able to “catch” any live accidents during the field testing. The field testing results however showed that false alarm was not an issue, and that is very encouraging. High false alarm rate is a common killer of the automated accident detection system, as people will get impatient and lose confidence if the system false alarms are frequent.

CHAPTER 4. SYSTEM ARCHITECTURE AND COMMUNICATIONS SYSTEM

4.1 System Description

The intersection accident detection system should have real-time capabilities in data recording, signal processing, and data communications. The real-time accident detection can be implemented using one of the following two system architectures:

- (1) Decentralized architecture
- (2) Centralized architecture.

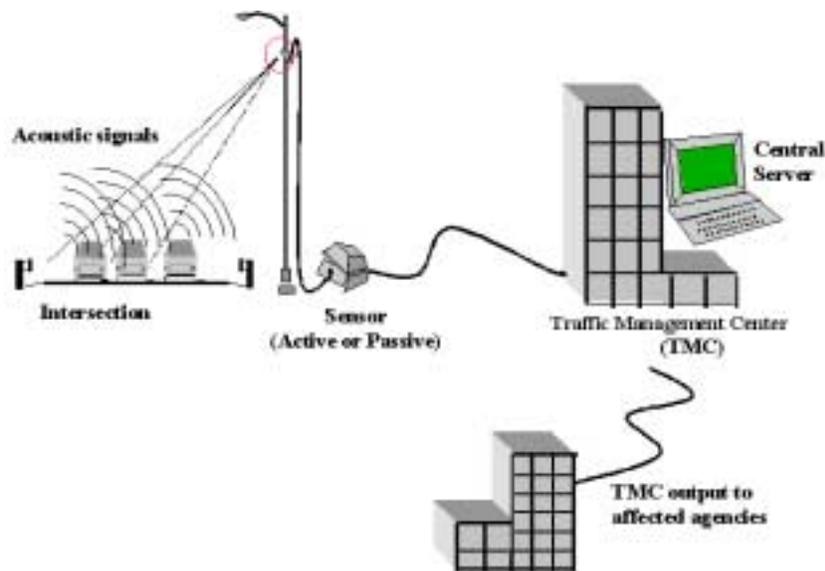


Figure 17 Real-time accident detection at intersection

The main difference between the two approaches is where the received acoustic

signals will be processed and what data will be transmitted to the traffic management center.

1. **Decentralized architecture** -This approach involves the use of active, or smart, sensors. The sensor is mounted on an existing overhead or intersection structure. The sensor not only listens to but also processes every received acoustic signal generated by passing vehicles or stationary (idling) vehicles in real time. The active sensor system is composed of a microphone, Digital Signal Processing (DSP) hardware, and communications hardware. The DSP hardware contains the automated accident detection algorithms, memory to store incoming acoustic signals, and a processor to apply the algorithms to the signals and output a “no accident” or “accident” warning. The communications hardware then transmits the warning to the traffic management center. With this approach, only minimal information will need to be transmitted from the intersection to a centralized location.
2. **Centralized architecture** -With this design, the main task of signal processing and accident detection is carried out on a central server at the traffic management center. The acoustic sensor mounted at the intersection is a passive acoustic (listen only) sensor. The sensors only task is to record the acoustic signal and transmit it back to the central server. Thus, the sensor is composed of a microphone and communications hardware. The central server contains the automated accident

detection algorithms, memory to store incoming acoustic signals, and a processor to apply the algorithms to the signals and output a “no accident” or “accident” warning. Once an accident is detected, a warning will be presented to the operator and then sent to affected agencies. By using centralized architecture, the local communications hardware has to periodically transmit the audio signal recorded at the intersection to the central server.

The decentralized design has particularly high operational requirements for the active sensors. Almost all of the signal processing is completed at the intersection. Each intersection has to retrieve data, video, and voice communications instead of a shared common communications architecture as in a centralized approach. However, the volume of transmitted data from the acoustic sensor to the central server is very low. Therefore, this approach has a very low requirement for the performance of the communications network and the central server. On the contrary, the centralized design has particularly high performance requirements for the communications network and the central server. A large volume of unprocessed signals needs to be transmitted from the acoustic sensor through the communications network, and then be processed simultaneously by the central server. The pros and cons of the two designs will be compared based on existing infrastructure deployment, cost, performance, reliability, and scalability.

4.2 Communications Mechanisms

Transmission of data between intersections and the traffic management center is an important component of the Real-time Intersection Accident Detection System. Communications technologies are comprised of wireline and wireless solutions. One way and two-way communications links that can be evaluated include wide area wireless communications technologies such as cellular phone, broadcast radio and TV, radio broadcast digital services (RBD), digital spread spectrum radio, satellite communications, etc. Wireline communications technologies can also be evaluated such as dial-up public telephone, Integrated Services Digital Network (ISDN), Synchronous Optical Networks (SONET), etc.

The current research on communications mechanisms provides investigation on Siemens OTN systems, which can incorporate voice, video, and data information from sensors and other field devices located at intersections and transfer the signals seamlessly via high-speed multi-megabit fiber optic cables. Research on wireless communications mechanism for the same purpose has also been conducted. The final selection on the communications infrastructure will depend on the cost of the deployment, scalability of the network, performance of the communications, the design structure and capacity requirements, as well as the ability to leverage the existing communications networks.

4.2.1 Wireline Communications System – Open Transport Network

(OTN)

4.2.1.1 OTN Architecture

MDOT currently is using Siemens Open Transport Network (OTN) as the fiber optic communications network in its transportation systems. OTN is a fiber-based system SONET for voice, data, LAN and video information. Its architecture is based on 4 major system components:

- The fiber optic backbone, on which all information of the equipment is multiplexed;
- The OTN nodes, which form the access ports to the network;
- The interface cards, which provide the user access to the system;
- The OTN Management System (OMS) for central network management.

Among the 4 system components, the interface cards provide communications between the optical rings and the applications we are interested in. OTN has 4 different interface cards for data applications, voice applications, Local Area Networks, and video applications, respectively.

1. Data applications: RS232, RS422, RS485, G703, V-series, point-to-point, multipoint, multidrop;
2. Voice applications: 30B+D, UP0, S0, G703 Digital, E & M, Public Address, 2Mbps, analog (2 / 4 wire);

3. Local Area Networks: Ethernet IEEE 802.3;
4. Video: PAL/NTSC, CVBS, M-JPEG Compression, Fixed/Switched

An OTN network is built up with nodes interconnected by a dual fiber optic ring. A network can consist of up to 250 nodes. It can extend over a couple of hundred meters up to 1,243 miles and more. The possible geographical extensiveness of an OTN network means a saving on modems and signal amplifiers. The OTN system can offer a capacity of 150 Mbps (OTN-150), 600 Mbps (OTN-600) and 2.5 Gbps (OTN-2500). Communications between OTN nodes in the ring is based on Time Division Multiplexing (TDM), allowing multiple users sharing the transmission medium on the ring. TDM divides the time domain into repetitive periods called frames, which are subdivided into time slots. These time slots are one bit long. The time slots are allocated to the user applications during which they can transmit user data. OTN-2500 system has a frame length of 31.25 μ s (one fourth of the 125 μ s frame used by telephone communications) and each frame contains 73,728 bits. Thus every time slot in a frame corresponds to a 32 kbps (=1 bit/31.25 μ s) system bandwidth. The bandwidth allocation to each application has to be on increments of 32 kbps. OTN guarantees direct access to the network at any time, avoiding long access delay and enabling real time applications. Each application has its own virtual connection because the transmission capacity on the backbone is allocated in a semi-permanent way, which means the allocated bandwidth is always available for that application, independently of other applications running on the network. New applications can be realized by simply adding additional interface cards, which are

allocated part of the available bandwidth of the backbone.

4.2.1.2 MDOT OTN System Implementation

The existing MDOT OTN network is OTN-2500 based and supports 2.5 Gbps bandwidth. For the time being, the network only consists of one node and is expected to expand to 2-4 nodes in the near future. Each node of the MDOT OTN system carries 2 fibers in and 2 fibers out. Each fiber has a bandwidth of 2.5 Gbps. Its double ring structure and redundant power and optic controls provide a highly resilient communications system. This structure allows the network to work around cable breaks and product failures, without affecting the devices connected to the nodes, thus achieving optimum network availability. The major application running in the current OTN network is video application. The OTN-2500 system is actually sufficient to support all present and future applications. The variety of the applications it supports is a unique feature of the OTN system. It enables the network to handle voice, data and video services all by one network via a single, reliable communications backbone. OTN makes sure all the information gets to the other end in a fast, transparent and reliable way.

The real-time intersection accident detection system is based on a crash detection and verification algorithm, with an audio-based component for automated crash detection using the approach described in [2], along with a video-based component for crash verification performed at the traffic management center after a crash warning is activated

by the detection system. This combined audio-detection/video-verification mechanism will be able to provide real-time crash warnings to the operators through its fast audio detection capability while it can also identify, through the video cameras, the nature and severity of the crash, which in turn determines the requirements of incident responses. The multimedia capability of the OTN network provides the bandwidth needed for the data + video transmission, facilitates direct, real-time access to the network, and ensures accurate, responsive, convenient detection on the accidents at the intersections.

4.2.1.2.1 Real-Time Audio-Based Accident Detection

In order to set up a service between interface ports of different nodes, bits are allocated in the TDM time frame. This time slot allocation reserves a permanent virtual connection between the two ports, thus providing a guaranteed transmission path between the communicating devices. The number of time slots allocated to continuous accident detection signal transmission depends on the bandwidth needed. The typical frequency of the audio detection signal is 11,025 Hz. The analog signal is sampled at 22,050 Hz and 8-bit resolution, resulting in 177 kbps payload data rate at each node. Real-time audio signal transmission from all 250 nodes (maximum) will generate about 48-56 mbps data traffic, which will not impose too much bandwidth burden on an OTN-2500 network. In the decentralized scenario, high processing power sensors have to be deployed at all intersections, which may lead to both scalability and reliability issues. Thus the

centralized architecture is the desirable option for accident detection at intersections if the transmission backbone is based on an OTN-2500 system.

The audio sensor at each intersection can be directly connected to the OTN data interfaced card. For an OTN RS232 data card, it can carry 12 ports and the maximum speed per port is 100 kbps. An OTN RS485 data card can be programmed to support different data rates up to 2 Mbps. Furthermore, an OTN system is also able to support structured G.703 service, which transmits data rates ranging from 64 kbps to 2.048 Mbps, supplied in 64 Kbps increments. Thus there are several options for transferring the real-time accident detection signals from the intersections to the TMC:

1. Split the traffic signal into several ports on a low speed RS232MM card or
2. Program a RS485 card to achieve the data rate for the accident detection signal transmission; or
3. Transmit it through a structured G.703 high speed data card.

Among the 3 possible options, RS485 features the most suitable interface card to carry the accident detection signals. The RS485 interface card is designed to interconnect RS485 busses via OTN. OTN allows RS485 networks to be created over large distances, without the use of repeaters. Each RS485 card has 3 independent ports. Payload data rates are programmable into the following values: 1.2 kbps, 2.4 kbps, 4.8 kbps, 9.6 kbps, 19.2 kbps, 38.4 kbps, 64 kbps, 93.75 kbps, 128 kbps, 187.5 kbps, 256 kbps, 384 kbps, 500 kbps, 1.5 Mbps, 2 Mbps. Among these values, 187.5 kbps fits into the need of the

required data rate. If the additional transmission overhead is counted, the number of bits per frame reserved for each data connection is 12. Thus the total bandwidth required for real-time accident detection at all 250 nodes will be $12 \times 250 = 3,000$ bits per frame, which is about $3,000/73,728 = 4\%$ of total capacity. The communications backbone has sufficient bandwidth to support centralized real-time audio-based accident detection for all the intersections.

The binary signals presented to the interface cards are inserted into the frame and further multiplexed into two outgoing optical fibers, with each running in the opposite direction providing 100% self-healing capability. In order for the control center to identify the signals from different intersections, the OTN system has its proprietary addressing format. The address is provided in the hierarchical structure such as <node number, card number, port number>. Based on the address information, the TMC can accurately identify where the signals come from (from which intersection and from which application) and route them to the corresponding TMC unit promptly for further processing.

4.2.1.2.2 Video-Based Accident Verification

Coding and compression techniques (e.g. M-JPEG) have provided the ability to reduce video transmission bandwidth requirements, thereby trading bandwidth for image quality. It is assumed that each video connection consumes 10-12 Mbps bandwidth

without compression. The network delivers acceptable video quality at a compressed data rate of 2 Mbps (e.g., using MPEG-4). Due to high bandwidth requirements on each video connection, TMC is not expected to support concurrent video monitoring on all sites. Imagine if the OTN system scales to 250 nodes and each node is equipped with real-time video surveillance. A bandwidth of $250 \times 12 \text{ Mbps} = 3.0 \text{ Gbps}$ is required, which is already beyond the maximum OTN-2500 capacity of 2.5 Gbps. The suitable interface card for the video application is the MPEG interface card. All MPEG cards have 4 video inputs, each with their own codecs, which can be transmitted simultaneously. The same MPEG card can also be used as an output board, which then has 4 independent output ports. The MPEG cards can offer a higher compression ratio than the M-JPEG coding, allowing a higher number of video connections to be transmitted through the same OTN.

We proposed the audio-detection/video-verification mechanism, which provides real-time audio signal monitoring but only activates video signal transmission when an accident alarm is received. In this way, the OTN network capacity will not be over-engineered. This is achieved by the unique video switching capability provided by the OTN system. Instead of monitoring all the nodes (e.g., 250) simultaneously, the traffic monitor center can switch among different remote site cameras and conduct time-sharing monitoring. A small number (less than 250) of high quality video buses are programmed on OTN, among which some are reserved for the advanced digital video detection and recognition. The bandwidth needed per video bus relies on the following

parameters: color depth, horizontal resolution, vertical resolution, and frames per second. The bandwidth per video bus on an MPEG card can be configured from 1 Mbps to 12 Mbps, depending on the above parameters. 2 Mbps is adequate for most video applications. Each video bus is associated with a video output port of an MPEG card. The operator can dynamically connect any camera from any intersection to any video output. This video switching capability on OTN provides the TMC operators with full access to all cameras without the burden of designing a fixed video network of matrices and switches or the burden of transmitting overwhelming video traffic.

4.2.2 Wireless Communications System

Wireless communications can extend the access ranges for the intersections that do not have easy access to the existing OTN communications infrastructure. Relying on wireless medium, data collection devices/sensors are electronically linked via wireless communications to a central base station server. Each sensor is equipped with a wireless modem to convert computer signals to radio waves, which can be propagated via the wireless medium to the base station. The base stations can be connected to the MDOT TMC through wireline communications medium, e.g., the leased telephone lines. A wireless modem at the base station then converts the radio waves back to computer signals for further wireline transmission. Due to the poor transmission quality and limited bandwidth availability on the wireless medium, decentralized architecture is preferred so

that a minimum amount of signals will be carried through the unreliable and precious wireless channels. There are several ways to implement the wireless communications in the real-time accident detection systems between the intersections and the base stations.

4.2.2.1 3G/4G Cellular Communications

The support of continuous transmission of the audio accident signals through the cellular network is almost impossible since there is no leased spectrum in the commercial cellular networks. By using the decentralized scheme, we assume only the alarm signal activates the transmission to the control center. Whenever an accident is detected, the local equipment will dial in and transmit one bit or two bits alarm signal to the base station, which propagates the alarm signals to the control center. Currently 3G wireless communications can support data rates up to 384 kbps. The use of cellular spectrum for erratic transmissions and high bandwidth video signals does not make the best or most efficient use of cellular communications infrastructure. So, further research needs to be conducted on how to carry the video based accident verification signals through the cellular networks. Future 4G cellular technology will be able to support data rates up to 500 Mbps, which is 250 times the maximum data rate promised for today's cellular network and makes the video transmission possible by then.

4.2.2.2 220 Mhz Land Mobile Communications

The FCC recently reallocated the 220 Mhz land mobile spectrum, resulting in many new channels, many of which have been auctioned to the public. The FHWA obtained temporary rights to five narrowband (in 5 kHz) frequency pairs in this band, which were set aside for ITS experimentation purposes. The permission for exclusive access to any of these 5 frequency pairs needs to be further applied. Due to the limitations of the bandwidth provided by the wireless medium, high-efficiency modems are needed in order to deal with impairments experienced in the wireless channel if the same quality of transmission is required. This represents a key technical challenge faced in the system. Fortunately, nowadays modulation and demodulation schemes used in the 220 Mhz frequency band can eliminate the noise along the wireless transmission, making the quality of transmission comparable to that of the wireline communications. The wireless modems at the intersections are polled periodically and pass audio signals to the transceivers located together. The base stations will pick up the wireless signals from the transceivers and then will forward the signals to the control center, through the leased telephone lines. The FHWA spectral allocation to ITS has not received much attention, and this may be due to the fact that certain ITS applications, such as video transmission, require data rates which cannot be supported on narrowband channels. More research needs to be conducted in this area. The overall performance and cost effectiveness of using wireless communications in this system can be evaluated through the next phase of

the project.

CHAPTER 5. FEASIBILITY OF REAL-TIME IMPLEMENTATION

The feasibility of real-world implementation was evaluated by examining the real-time testing performance of the system. We also looked into a number of other implementing issues, and a summary of the feasibility study is provided in this chapter.

5.1 Detection Accuracy

System reliability and performance is the most important issue. If a system shows a low detection rate and a high false alarm rate in lab testing, the eventual implemented system will more than likely fail.

Our system has showed a high detection rate in lab testing and limited field testing. Because it is very difficult to obtain crash signals, all these tests were carried out based on the current database with a limited number of crash signals, which may not be able to cover all typical crash sound features and thus could affect the accident detection rate. However, eventually more and more newly detected crash signals will be added into the database and that will definitely help expand and improve the crash signal database and further improve the accident detection rate. A low false alarm rate in lab testing and 0 false alarm rate in limited field testing is very encouraging. Furthermore, just like the case that the detection rate will improve with the expansion of the crash database, the

false alarm rate will also be improved as we add more and more normal crash signals into the database. Based on the system performance from multiple stages of testing, we feel confident that the system will have good reliability and performance when eventually implemented in the field.

5.2 Algorithms' Computation Time

We did the computational time testing using the same laptop as we used in the overlapping lab test (Section 2.2.2). The result showed that it takes on average 0.2 seconds to process one 3-second signal. That means in one 3-second sampling period we can analyze up to 15 input signals using the DWT scheme. In other words, using an ordinary laptop, we can process accident data from 15 intersections simultaneously with the DWT scheme, 5 intersections with the overlapping scheme, and many more intersections with the lifting scheme.

Currently, the detection algorithms are coded in MATLAB. Although MATLAB is user friendly and very easy to use, the code is not very efficient. The code written by other languages such as Visual C++ can be much faster. In addition, there may also be several other possible ways to improve the algorithm coding that can make the algorithm even faster. As computers become more affordable and much more powerful, we do not think computation time will become a major problem for real-world system implementation.

5.3 Communications Feasibility

Currently MDOT has already installed an OTN-2500 system that supports 2.5 Gbps bandwidth. This system is not fully utilized, and we can make use of this system to transmit audio traffic signals from intersections to the traffic management center. Take centralized system architecture as an example, as it has a higher requirement on data communications. As illustrated in section 4.2.1, assuming the analog audio signal is sampled at 22 KHz and 8 bit resolution, it results in 176 kbps audio data traffic at each node. Considering the upper bound of the system is 250 intersections, the maximum audio data transmission demand is only 44 Mbps, which is really negligible compared to the 2.5 Gbps system capacity. Besides, the system also has a unique feature of being able to handle voice, data and video services all by one network via a single, reliable communications backbone. Along with OTN system's dynamic video switching capability, we can realize the proposed audio-detection/video-verification mechanism under the current system's data transmission capacity.

The current deployed OTN-2500 system provides a very good basis for the implementation of Real-Time Accident Detection System, so we do not need to reinvent the wheel. This will significantly reduce the cost of accident detection system implementation. Besides, we can integrate the Real-Time Accident Detection System into the current traffic surveillance system, and make full use of the unused capacity of OTN-2500 system to transmit traffic sound data and use the traffic surveillance system to

confirm the detection results of our accident detection system.

CHAPTER 6. SYSTEM IMPLEMENTATION RECOMMENDATIONS

This chapter documents recommendations for system implementation. Recommended configurations of the real-world system are described in the following sections.

6.1 System Architecture

We recommend using the centralized system architecture. The reasons are the following:

1. Normally the centralized architecture is more economic than the decentralized system. Providing signal processing capability at intersection level sometimes means higher maintenance costs and lower reliability. On the contrary, simple sensor with basic signal collection and transmission abilities requires less maintenance and can be more robust.
2. Another reason is that the transmission of all the sampled raw audio signals at most takes less than 4% of the total system communications capacity, therefore there is no need to spend extra money to reduce the data transmission demand while paying a lot more for local signal processing.

6.2 Data Transmission

We recommend that the wireline data transmission be used for the following reasons:

1. Wireline method is compatible with the current MDOT OTN-2500 system.
2. The current wireless communications methods can not fully support our audio-detection/video-verification mechanism and the centralized system architecture. More research still needs be done on how to use the current wireless technologies to carry video-based traffic signal.

However, wireless communications may still be useful if the existing wireline communications facilities are not reachable, especially in some remote areas. Because of the relatively poor transmission quality and limited bandwidth availability on the current wireless medium, we suggest using decentralized architecture at these intersections so that the data transmission demand can be significantly reduced.

6.3 Algorithms

We recommend using the overlapping scheme for two main reasons:

1. A severe accident can cause inestimable property and life loss, and can also cause serious traffic congestion if the accident is not properly handled in time. For that reason, achieving high detection rate is always a very high priority. The overlapping scheme clearly provides the highest accident detection rate among

all three methods investigated and should be used.

2. As discussed in Section 5.2, even an ordinary laptop can handle the signal sampling, processing and classification procedure in real-time for a street system of reasonable size with multiple intersections. The relatively long computation time associated with the overlapping scheme should not be a concern for implementation.

6.4 Summary of Recommended System Configuration

In summary, the recommended system configurations are as follows:

- **System Architecture:** *Centralized Architecture*
- **Data Transmission Method:** *Wireline Transmission or more specifically, Siemens OTN-2500 system*
- **Algorithm:** *DWT + Overlapping Scheme*

A recommended real-time accident detection system is illustrated in Figure 18.

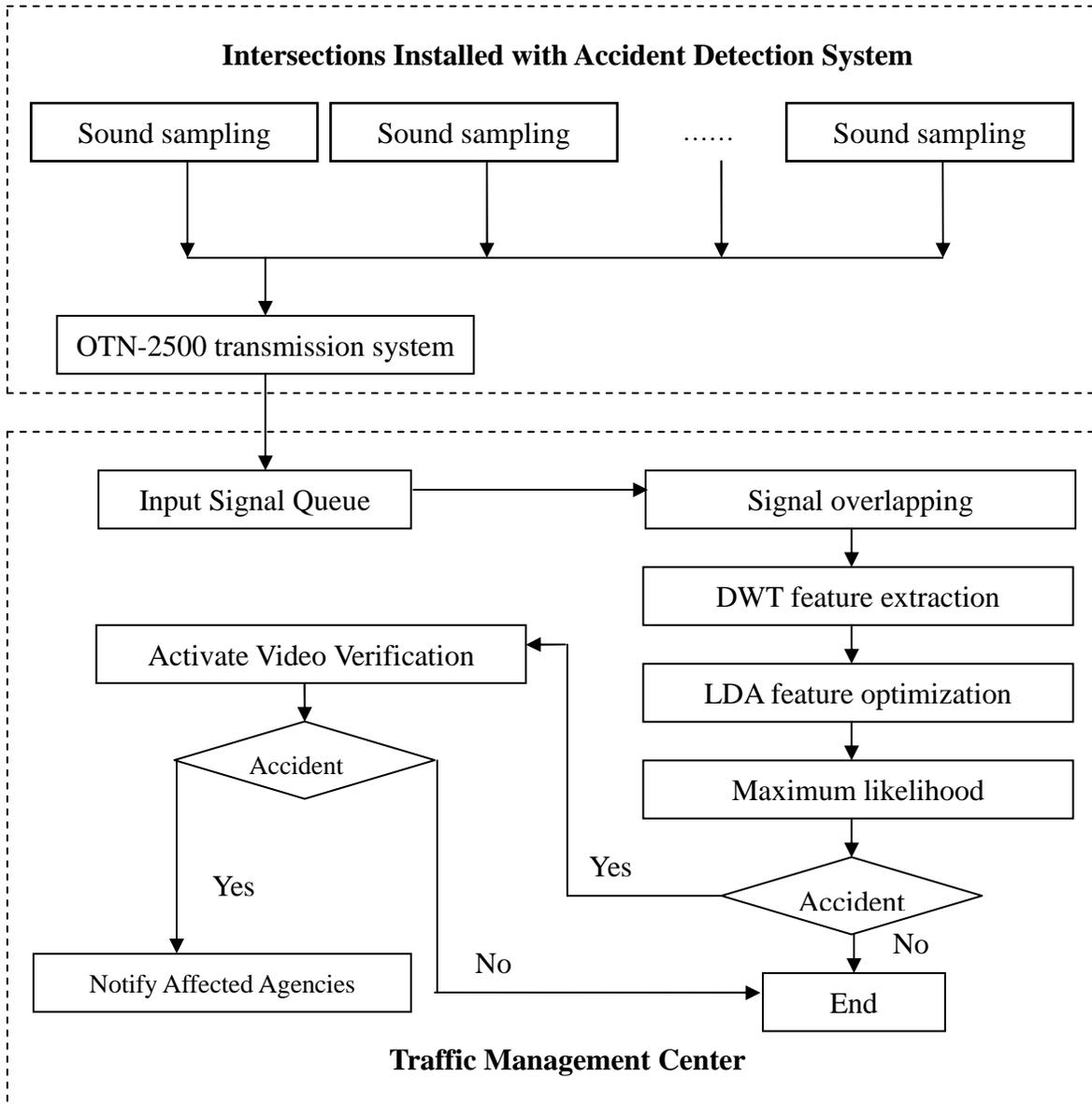


Figure 18 Recommended system diagram

CHAPTER 7. SUMMARY AND FUTURE WORK

7.1 Summary

In this research, we first went through the detection algorithms investigated in the previous phase of the project and focused our efforts on the major real-time implementation issues such as detection algorithm selection and improvement, real-time system performance, system architecture and communications system, and implementation feasibility.

Two detection algorithm improvements were proposed, namely the lifting scheme and the overlapping scheme. The lab testing and field testing were performed in real time and the results were compared with the baseline algorithm from the previous research phase. Among the three investigated schemes, the overlapping scheme has the highest detection rate and also the most computation time; the lifting scheme has the lowest detection rate and the least computation time; and the detection rate and computation time of the DWT lies between the overlapping scheme and the lifting scheme.

Two system architectures were investigated, which are centralized and decentralized respectively. We also investigated MDOT's current OTN-2500 communications system and various communications methods, including wireline system, 3G/4G cellular system and 220 Mhz land mobile communications system. The system architecture is closely linked to the communications method. The centralized system architecture has a higher

communications requirement for the communications network than the decentralized architecture, while the decentralized architecture has a higher requirement for the sensor installed at intersections than the centralized architecture.

Finally a recommendation was made for the implementation of the Real-Time Automated Accident Detection System at Intersections. The recommended system configurations are a Centralized Architecture with Wireline Transmission, with DWT+Overlapping Scheme as the signal feature extraction method.

7.2 Future Work

This research provides a preliminary study of the implementation feasibility of a Real-Time Accident Detection System at Intersections. In order to move the project into the implementation phase, there is still much work that needs to be accomplished.

1. **Software development and integration:** We need to design a software package to integrate the detection algorithms and interface with traffic management control center software and communications data flow. The package should be user friendly and open to future updates and changes.
2. **Communications network design:** Although we have accomplished a preliminary study of the communications system and made our recommendation, there is still lot of work ahead, such as the network topology design,

communications algorithms design, and communications quality and reliability analysis.

3. **Implementation cost estimation:** Even though we envision the system as an inexpensive one there is still a lot of work left in order to assess the implementation cost of a system of certain size. The cost will largely depend upon the cost of component integration and communications.
4. **Implementation testing:** The implementation testing will help us collect data on how the detection algorithm and communications network work together. Specifications such as the detailed hardware components and installation requirements are all essential to the success of a large-scale system implementation and need to be investigated. One example would be to determine the type of weather-proof microphone and its optimal placement location.

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