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OPTIMAL CHANNEL SELECTION FOR REAL-TIME UPLINK DATA TRANSMISSIONS IN AMBULANCES

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Through wireless internet access, ambulances take advantage of the widespread cellular coverage in rural and urban areas to transfer audio, video, and vital signs to the emergency room. In the current implementation adopted by the DREAMS™ ambulances, a designated channel is selected randomly. It is used to transmit high priority data, such as vital signs and audio. The remaining channels are used for video transmission. Whenever the communication system in the ambulance detects a certain threshold of packet losses in the designated channel, the communication system randomly switches the high priority data to another wireless channel. However, the designated channel selection process does not necessarily select the best available channel. The objective of this paper is to optimize this process through proportional-integral-derivative (PID) control and optimization with feedback. For each channel, an objective function is calculated. It includes a derivative term for fast response and an integration term for detection of small but consistent differences between channels, in addition to the proportional term. Using a causal real-time optimization algorithm, the maximum objective function is continuously selected. Thus, the proposed optimal channel selection algorithm enables the ambulance's communication system to intelligently shift the load to better quality channels without detailed information about the channels. The proposed algorithm combines key performance metrics (i.e., reliability and effective transmission rate), which can be calibrated with different weights. Using data from simulation and experiments in commercial cellular networks, we compare the performance of the ambulance with and without the algorithm to show dramatic improvements in the reliability and throughput of the ambulance's uplink transmissions.

Key words: wireless channel selection, mobile multimedia, digital ambulances, PID controller, heterogeneous networks, channel diversity, 3G
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1 Introduction

The Disaster Relief And Emergency Medical Services (DREAMS™) project [8], which is a partnership between the University of Texas Health Science Centre at Houston, the Texas A&M University System, and the U.S. Army Medical Research and Material Command, has implemented several ambulances that support real-time communication between the emergency medical technicians (EMTs) in the moving ambulance and emergency room physicians in the hospital. Thus, while a patient is being transported in the ambulance, the EMTs can communicate with hospital personnel. At the same time, the patient's vital signs and video images are transmitted in real-time to the emergency room (Figure 1).

This real-time data transfer of audio, video, and vital signs is possible through wireless internet access. Taking advantage of the widespread cellular coverage in rural and urban areas, the ambulance transfers data to the Internet and then to the hospital. At any instant, the ambulance will be transferring data if it manages to get connectivity on its way. In case communication is lost, the ambulance has the capability to store the high priority data (such as vital signs and audio) to be resent later. Of course, the amount of data stored and resent later is limited.

Figure 1. Voice, data, and video communications between EMTs in the field and ER physicians [8]

The communication system in the ambulance includes a system with several third generation (3G) wireless cards from different cellular service providers [26]. Apart from exploiting the benefits of different service providers, it can also take advantage of the different technologies available and the channel diversity characteristics (i.e., using two channels from the same carrier's tower simultaneously) while on its way. Figure 2 illustrates how the ambulance takes advantage of the cellular coverage in a given area by using different service providers. The pool of channels in use at a given time varies as the ambulance moves along the road.

Some problems for this system of several wireless interfaces are inherited by the dynamic behaviour of the wireless channels. As described in [6], "Wireless channels change over time in unpredictable ways due to location environments, user movement, or other interferences". Large and small-scale propagation effects and handoffs to different cell towers and/or different providers can limit the throughput as the ambulance travels at high speeds (e.g., 90 miles/hour) [25].

In addition to the challenges created by the dynamic nature of the wireless channel and the high-speeds that the ambulance typically travels at, real-time data transmission for ambulances is critical at the uplink. Third-generation cellular communications are asymmetric, with higher transmission rates on the downlink, i.e., from the hospital to the ambulance. For instance, in CDMA/HDR (High Data Rate), also known as EV-DO, the downlink capacity is expected to be three or four times greater than the uplink capacity for data-only applications [3]. Since most of the information flows from the ambulance to the hospital, the uplink transmission rates will be the main limiting factor in our system.

The aforementioned challenges are combined with the critical nature of the data sent from the ambulances. The data must be sent reliably, with low delays and no interruptions. Every detail of the transmitted data (e.g., a portion of the audio transmission or a portion of the vital signs data) must be correctly received by the doctors at the emergency room. Therefore, data transmission for ambulances is a very special case of wireless real-time data application transmitted from a fast moving node, with critical quality of service (QoS) requirements. Similar to communications systems that employ mobile access routers (MARs) [26], the network resources available to the ambulance come from multiple cellular channels from different providers or technologies, with limited bandwidth and scarce information of the channel quality parameters. This combination justifies the need for dedicated algorithms that target data transmissions for ambulances.

In particular, our experiments with the DREAMS™ ambulances also showed that there are limitations in its current implementation, which uses a designated channel selection mechanism based on availability only. A designated channel transmits high priority data, such as vital signs and audio; the remaining channels are used for video transmission. Whenever the communication system in the ambulance detects a certain threshold of packet losses in the designated channel, the communication system randomly switches the high priority data to the next available wireless channel. This process for the selection of the designated channel can be improved. In theory, the communication system in the ambulance should have the capability to shift the load to better quality channels to dynamically provide efficient and reliable service to the users.

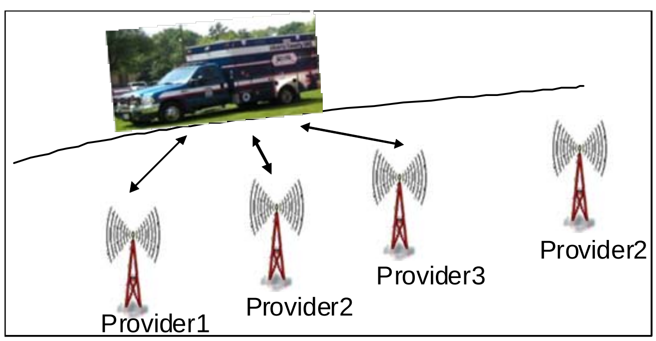

Figure 2. Provider and channel diversity

Our goal is to enhance the intelligence of the current communication system operating in ambulances such as the ones implemented in the DREAMS™ project. An innovative way of selecting the designated channel using network performance metrics and a proportional-integral-derivative (PID) [10] selector is our main contribution. We focus mainly on the uplink behaviour of multiple cellular channels and the network conditions, using feedback information from real-time data packets. For each uplink channel, an objective function is calculated. Then, a causal real-time optimization algorithm selects the maximum objective function and thus optimally selects the best wireless uplink channel as the designated channel.

As opposed to traditional channel selection mechanisms used for cellular handoff schemes [25], power is really not the most important factor; rather, the effective transmission rate and packet loss rate are considered in our objective function. Furthermore, the weights for transmission rate and packet loss rate can be calibrated, depending on which factor is most critical.

Control theory has been extensively used in wireless communication systems. In particular, the power control of such systems has been studied over the past fifteen years with many important contributions [7, 12, 13, 14, 27, 29]. However, to address the specific needs of the DREAMS™ ambulances' communication system, our proposal to apply control theory considers transmission rate and loss rate as the most important factors. Previously, we conducted an initial study that used low-pass filters that average and combine the values of transmission rate and reliability. The drawback of this system is that the low-pass filters caused delay to the data used in the objective function [28]. To reduce the effect of noise and to avoid unnecessary switching of the designated channel, a derivative term and an integration term are introduced in this paper. These terms have been added to our algorithm to make it a PID channel selector. The PID selector improves the criteria of channel selection because it takes into consideration fast-fading effects.

Moreover, the effectiveness of the designated channel selection scheme is validated using real metrics of transmission rate and reliability. We performed several experiments in a commercial cellular network, including a statistical study to evaluate the performance of real-time and constant rate UDP traffic [15, 31]. To show the effectiveness of the PID selector, in this paper we use samples of data collected from those experiments.

The remainder of the paper is organized as follows: Section 2 reviews the background information and discusses related research work; Section 3 introduces the optimization function with feedback based on the performance metrics such as transmission rate and reliability; Section 4 describes the proportional-integration-derivative process that is added to the evaluation of the objective function; Section 5 presents the main results of the optimization method proposed to be used for designated channel selection. Finally, Section 6 contains the conclusions and discussions on future research plans.

2 Background and Related Work

In this section, we first describe the network model of the DREAMS™ ambulance communication system. Then, we discuss related research on mobile healthcare applications and channel selection mechanisms.

2.1 The ambulance's communication system

Real-time communication between the ambulance and hospital occurs in three forms:

1) vital signs from the ambulance to the hospital, including heart beat rate, blood pressure, temperature, and electrocardiogram waves;
2) audio packets from/to the ambulance to/from the hospital;
3) video packets from the ambulance to the hospital, including images of the patient.

The data flow from the direction of the ambulance to the hospital is shown in Figure 3. First, the data in the ambulance is sent to the wireless network cards in the ambulance's communication system. The wireless network cards transmit data through the wireless links to the providers' cellular tower, shown in Figure 3 as a generic wireless network. From the wireless network, data is transmitted to the Internet, and then routed to the hospital. This way, a point-to-point data link connection is established between the ambulance and the hospital. At the hospital, data arrives to a receiving buffer and is finally delivered to the applications running in the hospital's computer.

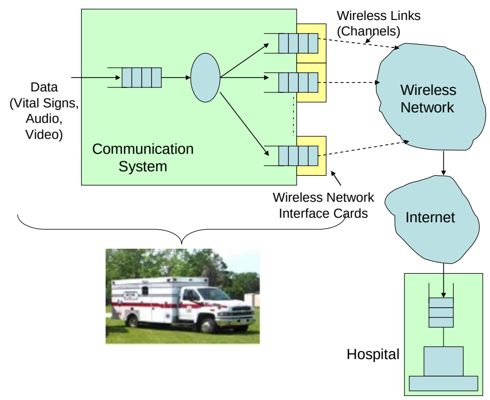

Figure 3. Flow of data from the ambulance to the hospital

Because of the real-time requirement of this communication system [30], the transport of data is done using the User Datagram Protocol (UDP) [24]. In this research problem, real-time data consists not only of audios and videos, but also vital signs. Vital sign packets delivery must be guaranteed whenever possible; therefore, an application running on top of UDP keeps track of all the vital signs packets received by getting acknowledgements. This provides a more reliable UDP service [20]. Consequently, packet losses can be detected and the missing packet can potentially be retransmitted, within a certain timeframe.

2.2 Related Research

The performance of real-time data transmission for ambulances using 3G cellular communications has been addressed in several publications. Using simulations based on the OPNET™ network simulator, the performance of an uplink 3G system for mobile healthcare application is studied in [18]. The impact of buffer size on QoS metrics including jitter and packet loss rate are studied in [20] with a real test setup with an ambulance. There are also other implementations of wireless healthcare applications, such as a mobile clinic [11], a tele-consultation system using ambulances [19], and mobile communication systems used by the military [22]. Given its importance and complexity, this paper focuses on the problem of optimally selecting the best channel among a pool of channels available to the communication system in the DREAMs ambulance, using both simulation and experimental data.

Related research in the subject of link or channel state monitoring has been applied in scheduling algorithms such as the channel state dependent packet scheduling (CSDPS) described in [5], which takes into account the wireless channel conditions to schedule the transmission of different traffic sources into a single wireless channel. Overall, this topic of scheduling based on channel conditions (or channel awareness) has been extensively studied [4, 5, 9]. As stated in [3], "Channel measurement, channel control, and interference suppression and mitigation are three principles that can greatly improve the performance of a communication system, wired as well as wireless".

Typically, the focus of other studies on real-time data transfers over a 3G network has been on the forward (downlink) wireless channel. For instance, the work in [1] addresses the end-to-end video streaming over 3G cellular systems. The authors proposed a rate adaptation scheme based on TCP friendly rate control. Performance metrics of packet loss rate and round-trip time (RTT) were collected from the real-time transport control protocol (RTCP) packets and combined to determine a streaming rate for video transmission on the downlink channels. In [19], an approach to select different downlink channels by efficient feedback mechanism was proposed so that the feedback packets do not cause an overload in the uplink channels. The proposed channel selection scheme was applied to a cellular tower or a base station and the dynamical assigning of channels to users based on the quality and data rate of the channel was illustrated. More recent work focusing on Quality of Service (QoS) and downlink traffic delivery based on channel conditions has been applied to broadband wireless systems such as IEEE 802.16/WiMax [16].

Finally, our work combines effective transmission rate and reliability in an objective function that is used to select the best performing channel. This idea of combining several network performance metrics has been considered as a good tool to characterize the overall performance of a network. In a similar way, the work in [2] applies a "power" function that aggregates key performance metrics (e.g., delay, throughput) to provide QoS to telemetry applications.

3 Optimization with Feedback

In order to improve the baseline wireless communication system currently used in the ambulances, one must first establish a solid performance metric that can be used to compare the results of different designs. There are three main factors that one uses in the evaluation of the overall performance of the wireless communication system in the ambulances: the actual or effective transmission rate in bits/second; the reliability, defined as

$$R = 1 - packet\ losses\ \% \tag{1}$$

and the monetary cost. In this paper, the focus is on the first two factors, i.e., the transmission rate and reliability.

The effective transmission rate and reliability depend very much on the transmission rate and reliability of the communication system outside of the ambulance's communication system, e.g., the wireless provider's backbone network, and the Internet. In other words, the low data rates and/or reliability could be a result of either the selection of the wireless communication channels in the ambulance or the low data rates and/or reliability of the external communication system.

Thus, considering the communication system outside the ambulance as a "black box", we propose a way to enhance the intelligence of the current communication system in the ambulance and how it selects the best wireless uplink channel as the designated channel. The objective is to select the designated communication channel in the ambulance such that the following performance metric J is maximized

$$J = W_1\sqrt{Tx} + W_2\sqrt{R} \tag{2}$$

where, W_1 and W_2 are the weights for transmission rate and reliability; *Tx* is the transmission rate (bits/sec); and *R* is the reliability.

Since the goal is to maximize objective function *J*, the square root function is used. This choice of non-linear objective function allows us to avoid a choice of a combination of extremely high value of one variable and extremely low value of the other. The selection of weights W_1 and W_2 must be based on the experience of experts.

3.1 Initialization

The current DREAMS™ communication system randomly selects a communication channel and will only switch to the next channel when the system detects a certain threshold of packet losses in the designated channel being passed. The main data monitored is the packet transporting the heartbeat rate. Therefore, whenever the channel fails a simple heartbeat check, a new communication channel will be selected for the high priority data. The heartbeat check is basically a criterion related to reliability. If less than 3 echoes in 5 seconds are received, then one can conclude that there is no heartbeat for this channel. This channel selection method is apparently not optimal since it does not take the transmission rate into consideration or compare the loss rate for different channels.

In order to optimize the objective function *J* in Equation (2), more information on each channel is needed. Instead of randomly selecting the designated channel, small test packets are sent through each channel every 0.1 seconds in the beginning for 1 second. Based on the time it takes to transmit the packets and the measured packet losses for each channel, the best channel to send vital signals and audio signals can be determined. In other words, the designated channel is the one with maximum *J* value. This completes the initialization process. If a channel has packet loss rate above a certain threshold, it is assumed that the channel is lost. In this case, the lost channel will stay in "Initialization" mode. Small test packets will be sent through the lost channel once in every minute.

3.2 Estimation of Transmission Rate

For the channels that passed the initialization process, the transmission rate for channel *i* is estimated by

$$T_i(k) = aT_i(k-1) + (1-a)\,\frac{p_x}{t_x} \tag{3}$$

where $0 < a < 1$, *i* is the channel number, $T_i(k)$ is the estimated transmission rate at time *k*, and t_x is the time it took packet *x* with size p_x (in bits) to be transmitted to the final destination (i.e., the hospital). This is basically a low pass filter with p_x/t_x as input. This filter can be initialized with $T_i(0) = p_1/t_1$, where p_1/t_1 is the transmission rate of the first packet. Notice that the estimated time to transmit (ambulance to hospital only) is used instead of using the round-trip time (RTT) to estimate the transmission rate.

It is important to understand that the estimation for the transmission rate for each channel is a relative measure. The real transmission rate is more difficult to get. When a packet is sent, the time is recorded using the clock of the computer in the ambulance. When an acknowledgment is sent from the hospital, the time stamp is based on the clock of the computer in the hospital. There may be a difference between the clocks in the hospital and the ambulance. However, it is reasonable to assume that the difference between the two clocks is constant. The relative measure is used to simplify the implementation, i.e., to avoid the synchronization of the two clocks, which requires more complicated and costly communication system.

There is one issue with this relative measure of transmission rate: when the clock in the hospital computer is significantly slower than the ambulance computer, the estimated transmission rate could be negative. This will cause problem for the optimization of the objective function J since it cannot handle negative numbers. To solve this problem, we look at the relationship between the estimated transmission rate and the difference between the two clocks. Denote the time the packet p is sent by t_s (i.e., the time based on the clock in the ambulance computer), and the time the packet is received by the hospital by t_r (i.e., the time based on the clock in the hospital computer). Assume for instance the ambulance computer clock is t_d seconds faster than the hospital's computer clock. In other words, when the data packet is sent, the clock in the hospital computer is t_s-t_d. The real transmission time is determined by

$$Rx = \frac{p}{t_r - (t_s - t_d)} \tag{4}$$

Suppose the transmission rate has a range of [Rx_{min}, Rx_{max}]. From equation (4), one can derive

$$Rx_{\min} \le \frac{p}{t_r - (t_s - t_d)} \le Rx_{\max} \tag{5}$$

The above inequalities can be rewritten as

$$t_s - t_r + \frac{p}{Rx_{\max}} \le t_d \le t_s - t_r + \frac{p}{Rx_{\min}} \tag{6}$$

The clock difference t_d can be estimated as

$$t_d = t_s - t_r + \frac{p}{Rx_{\min}} \tag{7}$$

If the minimum transmission rate Rx_{min} is not available, then the following estimation for the clock difference can be used

$$t_d = t_s - t_r + RTT \tag{8}$$

Equation (8) can be derived from equation (7) by assuming that the time it takes the acknowledgment to be transmitted from the hospital to the ambulance is negligible. Equation (7) and/or (8) can be evaluated whenever a packet is transmitted. The smallest t_d will be used as the estimated clock difference, i.e.,

$$t_{d0} = \min_i (t_d(i)) \tag{9}$$

Using equation (9), the following estimation for Rx can be derived:

$$Rx = \frac{p}{t_r - (t_s - t_{d0})} \quad (10)$$

with a guaranteed positive estimated transmission rate.

3.3 Estimation of Reliability

The reliability of each channel can be estimated if 10 echoes are sent every second for each channel. The initial value for reliability is set to $R_i(0) = r_1/s_1$, where r_1 is the number of returned echoes, and s_1 is the total number of echoes sent during the initialization period. The reliability of channel i is estimated by

$$R_i(k) = bR_i(k-1) + (1-b)\frac{r_i}{s_i} \quad (11)$$

where $0 < b < 1$. Equation (11) is updated every second.

4 PID Selector

Clearly, it is desirable to use the channel that maximizes the performance metric J as the designated channel. However, initial evaluation of the objective function in Equation (2) shows that further improvement is necessary. In this section, simulated data is used to explain the rationale for applying a proportional-integral-derivative (PID) control to the objective function.

4.1 Simulation setup

To evaluate the initial performance of the channel selection mechanism described in Section 3, simulation experiments were performed using the network simulator ns-2 [21]. In order to collect information on the channels, in our simulations we send probe packets (small 56-byte packets) every 0.1 seconds. Acknowledgement packets are sent by the receiver, which allows the calculation of the metrics of transmission rate and reliability for each channel in the ambulance. The objective functions are updated every second.

The simulation is set up such that channel 2 has a constant data transmission rate during the entire simulation time. Channel 1 has a slightly higher data transmission rate than channel 2 from 0 to 240 seconds and from 400 to 600 seconds. Between 240 and 400 seconds, channel 1's data transmission rate dropped to a very low level, i.e., to simulate the effect of a congested link. To simplify the calculation, the loss rates are set to be the same constant value for both channels during the entire simulation time (e.g., 10 percent of packet losses). The simulation is set up to see if the optimal channel selection can choose channel 1 from t =0 to t = 240, switching to channel 2 after 240 seconds, and back to channel 1 after 400 seconds.

4.2 Trade-off between robustness and response time

The upper half of Figure 4 shows the values of the two objective functions defined in Equation (2) for the two wireless channels. It is clear that channel 2 is a better choice between 240 and 400 seconds, but in other times, noise in the signals can cause the selected channel to be switched back and forth between channel 1 and channel 2.

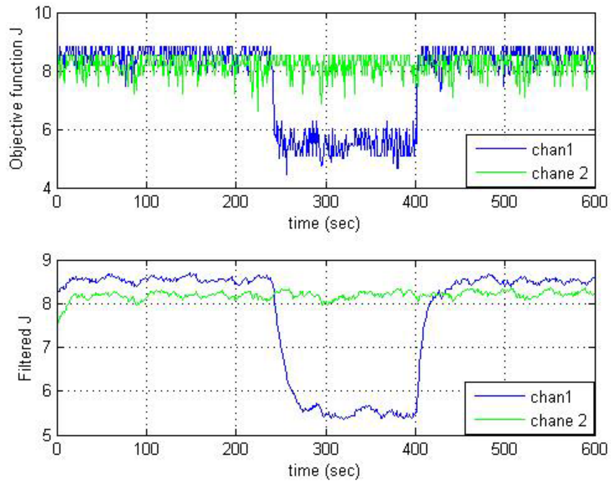

Figure 4. Raw data vs. filtered data

In order to avoid selecting the wrong channel and unnecessary frequent switching of the designated channel, the following low-pass filter can be used on the objective functions for each channel to reduce the impact of noise,

$$J_P^i(k) = cJ_P^i(k-1) + (1-c)J^i(k), \qquad i = 1,2,3,..., N \tag{12}$$

where, $J^i(k)$ is the raw objective function for the *i*-th channel as defined in equation (2), $J^i_P(k)$ is the filtered objective function for *i*-th channel; and N is the number of channels. The designated channel d is selected such that,

$$J_P^d(k) \geq J_P^i(k), \qquad i = 1,2,3,..., N \tag{13}$$

In the bottom half of Figure 4, the objective function was calculated for both channels using the weights W_1 = 0.6 for the transmission rate, and W_2 = 0.4 for the reliability, as in Equation (2). Using the filtered objective function in Equation (12) (with c = 0.9), the channel selection becomes straightforward.

The introduction of a low pass filter, however, causes delay to the signal. This delay can have significant effect when the signal has an abrupt change. This is illustrated by the simulated result in Figure 5, where at time t = 240 seconds, the deep fading in the quality of channel will not be detected quickly because of the delay effect of the low pass filter. The trace labelled as P is the filtered objective function. The addition of a derivative terms helps to reduce the delay. The proportional and derivative (PD) objective function is defined by the following equation

$$J_{PD}^i(k) = J_P^i(k) + c_d[J^i(k) - J^i(k-1)] \tag{14}$$

which is a linear combination of the proportional and derivative terms. The channel selection is still determined by Equation (13) with $J^i_P(k)$ replaced by $J^i_{PD}(k)$. The trace labelled as PD has an improved response time compared to the trace P.

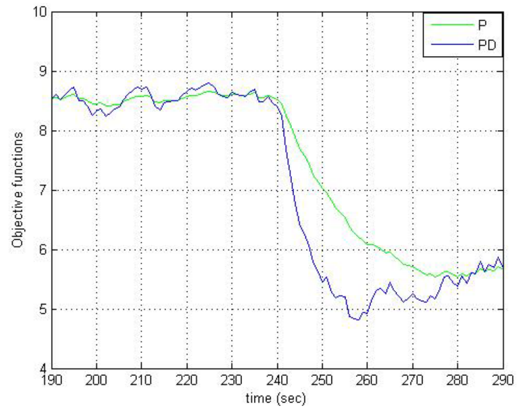

Figure 5. Proportional vs. proportional and derivative

An integration term is further introduced such that when there is small difference between two channels, the accumulated effect will lead to the selection of the better channel. The sum of the proportional terms over certain period of time, for instance, 20 seconds, is calculated and added to the PD term defined in (14) to give the following PID objective function

$$J_{PID}^{i}(k) = J_{P}^{i}(k) + c_d[J^i(k) - J^i(k-1)] + c_i \sum_{n=i-20}^{i-1} J^i(n) \tag{15}$$

where c_d and c_i are the weights for the derivative and integration terms. The same simulation setup for Figure 4 is used to illustrate the effect of using P, PD, and PID objective functions. To illustrate the effect more clearly, instead of the P, PD, and PID objective functions, the differences between the corresponding objective functions for channels 1 and 2 are plotted in Figure 6. The parameters for the PID objective functions are chosen to be c_d = 0.9 and c_i = 0.1. Since the difference between the objective functions of channels 1 and 2 are plotted and the channel with larger objective function should be selected as the designated channel, one should select channel 1 if the difference is positive and select channel 2 if the difference is negative. The effectiveness of the three objective functions can be analyzed in two aspects: the absolute value and the response time. The P type objective function has a slow response time when the deep fading of channel 1 occurred. The PD type has a fast response time for the detection of deep fading of channel 1, but on several occasions the value crossed 0, leading to wrong channel selections.

The PID objective function works the best among these three objective functions. The PID objective function has a fast response time, comparable to that of P objective function, during the deep fading of channel 1. It is further away from 0 than the P and PD types of objective functions. This implies fewer mistakes in channel selection than the P and PD objective functions.

Based on the above analysis, the PID objective function will be used for optimal channel selection. Notice that the P and PD types of objective functions are special case of PID with the coefficient of I and D or I terms set to zero.

Other techniques, such as adding a hysteresis to the channel switching condition, e.g., the designated channel is switched only when a different channel is better than the current one, for more than 0.05 in the PID objective function. Excluding certain channels from being selected as the designated channel if the transmission rate is too slow or the reliability too low can further improve the channel selection algorithm.

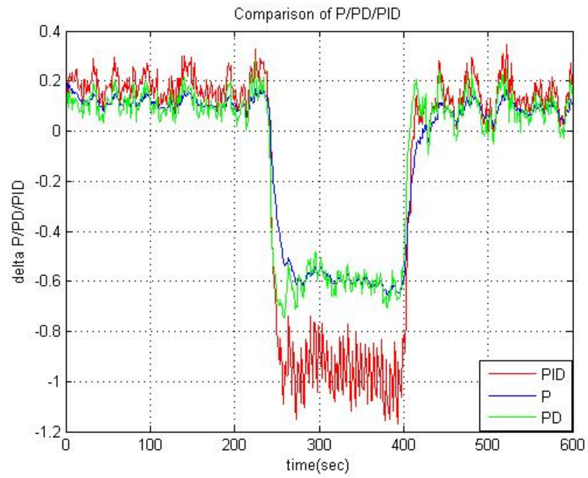

Figure 6. Comparison of P, PD, and PID objective functions

5 Experimental Results

The optimal channel selection algorithm developed in the previous sections worked well in the simulation environment. Next, we use experimental data to show the effectiveness of the algorithm.

A 3G wireless data card based on CDMA/HDR technology [3], also known as 1xEV-DO, was used for the tests. The card is a Sierra Wireless AirCard 597A. To emulate real-time traffic, we performed our experiments using constant-rate UDP traffic. This traffic was generated using a network performance tool called Iperf [17], which runs as a client/server application. An Iperf client, installed at a mobile computer with the 3G wireless data card, sends fixed-size packets (500-byte packets) over the cellular network to an Iperf server, which is a fixed Internet node. This experiment lasts for 10 minutes. Both the actual transmission rate and packet loss rates are recorded during this interval. In order to compare multiple channels, we combined different measurements taken at different times of the day, or different weather conditions.

In Figure 7, channel 1's average transmission rate and packet loss rate are 675.5 kbps and 0.26 percent for the 10-minute test. For channel 2, the average transmission rate and packet loss rate are 424.5 kbps and 1.14 percent. Based on the mean values, channel 1 seems to be the best option for the designated channel. However, between approximately 330 and 370 seconds, channel 1 is actually providing lower data rates than channel 2, with values in the order of 200 kbps. With our algorithm, this feedback information in the form of bandwidth and packet loss rate measurements will provide the ambulance's communication system with estimates of the actual performance of each channel.

Then, the channels' PID objective function can be periodically calculated. Based on the channels' PID objective functions shown in Figure 8, at any time between 0 and 330 seconds, Channel 1 would be the designated channel because it has the highest PID objective function. At time t = 330 seconds, the designated channel would be switched from Channel 1 to Channel 2. Then, at time t = 416 seconds, Channel 1 is selected again as the designated channel. This illustrates how our optimization algorithm takes advantage of the high performing channels, as opposed to the baseline system, which randomly selects one of the channels.

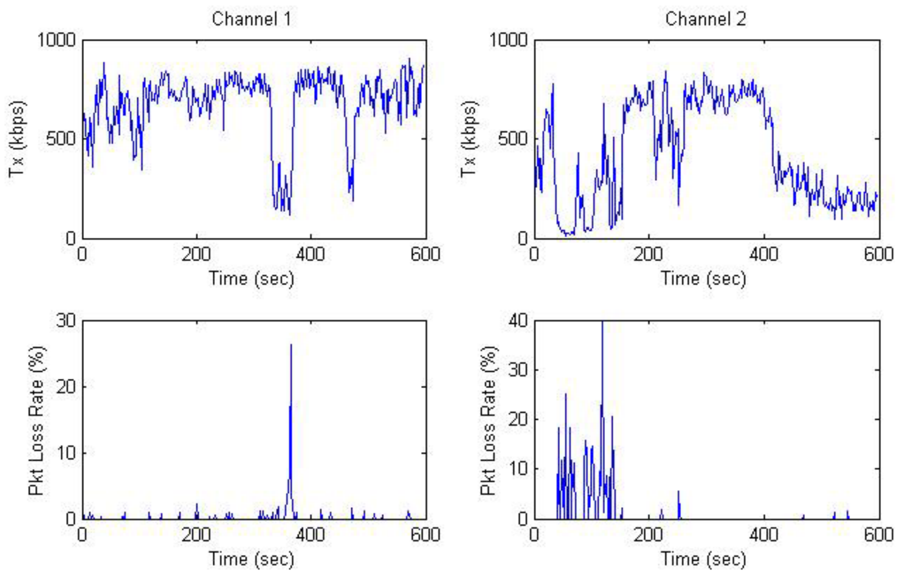

Figure 7. Measurements of effective transmission rate and packet loss rate on the uplink channels of a 3G network

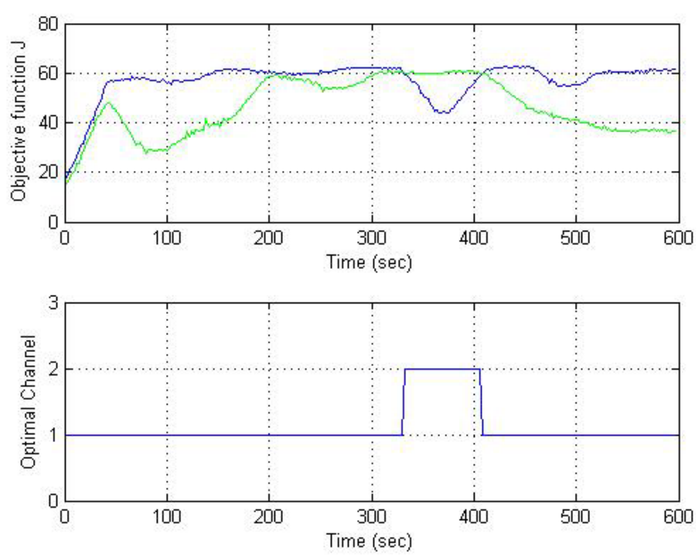

Figure 8. Optimal channel selection decision

The performance improvements of our scheme are shown in Table 1, which contains the average data rate and packet loss rate experienced by the user with and without our optimal channel selection mechanism. For the transmission rates, we also show in Table 1 the minimum and maximum transmission rates; for the packet loss rates, we have the peak loss rates which usually occur for short period of times and can be very different from the average packet loss rates.

Table 1- Performance comparison.

	Mean Tx	Min Tx	Max Tx	Mean Pkt Loss Rate	Max Pkt Loss Rate
Channel 1	679.5 kbps	118 kbps	904 kbps	0.26%	26.21%
Channel 2	424.5 kbps	12 kbps	840 kbps	1.14%	39.65%
With Optimal Channel Selection	705.1 kbps	190 kbps	904 kbps	0.08%	2.25%

Without the optimal channel selection, Table 1 presents the statistics for channel 1 and channel 2, assuming that one of them would be randomly selected as the designated channel. For instance, if channel 1 were selected, the transmission rates would range from a minimum of 118 kbps to a maximum of 904 kbps; however, the ambulance could experience peak packet loss rates of up to 26.2 percent. With the proposed designated channel selection algorithm, the minimum transmission rate during that 10-minute interval improves from 118 kbps to 190 kbps. The maximum transmission rate remains the same (904 kbps) which reflects the bandwidth of the best performing channel. As a result, the average transmission rate is now much higher (705.1 kbps) than if any single channel had been randomly picked.

Moreover, the packet loss rate reduced dramatically to an average of only 0.08 percent. With the proposed designated channel selection mechanism, the peak packet loss rate is only 2.25 percent. The peak packet loss rates of 26.21 percent and 39.65 percent of channels 1 and 2 were completely avoided, which results in a much more reliable data transmission from the ambulance to the hospital. In other words, by switching from channel 1 to channel 2, the periods of burst packet losses shown in the bottom of Figure 7 did not impact the performance of the ambulance's communication system.

6 Conclusions

In this paper, we presented a practical application of a real-time mobile multimedia communication system used in the healthcare field: the DREAMS^{TM} ambulances, which simultaneously use several wireless 3G cards to communicate with the emergency room. To improve the current communication system in the ambulance, we adopted a unique approach to use control theory and optimization with feedback to select the most reliable and fast wireless channel for the high priority data (i.e., vital signs and audio). An objective function that takes the transmission rate and reliability into consideration is proposed for optimal channel selection. The objective function includes a derivative term for fast response and an integration term for detection of small but consistent differences between any channels. The significant improvement made since the initial result was published in [28] makes it closer to the implementation of the proposed optimal channel selection for wireless communication in ambulances.

Like any other optimization problems that involve multiple performance indices, the channel selection result using the algorithm proposed in this paper is highly dependent on the selection of the objective function. With reasonable requirement on the user experience, the channel selection algorithm in general provides much improved results over the random channel selection scheme used in the current DREAMS™ ambulance. The effectiveness of the proposed optimal channel selection is shown with both simulation and experimental data obtained over a commercial 3G cellular system.

Unlike many optimization algorithms, the algorithm in this paper does not require extensive search over many possible solutions. Instead, at each time instance, the objective function is evaluated for a limited amount of channels (in the DREAMS™ ambulance, there are six channels) and the channel that maximizes the objective function will be selected as the optimal channel. This is basically a one dimensional search over the available channels. As a result, the computational time required for channel selection is negligible. There are drawbacks with the algorithm. First, random noises in the communication system can affect the result. To counter that, a proportional-integration-derivative process is added to the evaluation of the objective function. The price one has to pay is the slower response to the change of channel characteristics. In other words, if one channel changes suddenly, it takes the algorithm some time to respond. However, in such a case, no algorithm can completely avoid the delay of response. There is always a trade-off between fast response and robustness against noises.

Future research work includes the extension of this scheme to cover not only the designated channel, but to optimally select channels to be used by each data packet including the video signals. This extension is non-trivial since the data packets have different priorities.

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