# PERFORMANCE EVALUATION OF LOW RATE WPANS FOR MEDICAL APPLICATIONS

Nada Golmie, David Cypher, and Olivier Rebala
National Institute of Standards and Technology
Gaithersburg, Maryland

## ABSTRACT

*In this article we consider the emerging low-rate wireless personal area network (WPAN) technology as specified in the IEEE 802.15.4 standard and evaluate its suitability for medical applications. The main objective for this effort is to develop a universal and interoperable interface for medical equipments. We focus on scalability issues and the need to support several communicating devices near a patient's bedside. Given the nature and the diversity of the clinical environment, it is most likely that different medical applications will use different wireless technologies. We choose to quantify the performance of IEEE 802.15.4 devices in the presence of IEEE 802.11b devices since it may be the technology of choice for most web access, email, video, and printing applications.*

## INTRODUCTION

In medicine, providing timely access to complete patient information is key to saving lives and improving the overall safety of a patient's care. While better recording and reporting systems have been developed to provide a wealth of healthcare data, the information remains fragmented and largely inaccessible. Even within hospitals and large medical groups, when patients see multiple providers in different settings, no one seems to have access to complete information.

While many hospitals today are in the early stages of using data from all of the patient connected medical devices, connections are mainly based on the RS-232 port interfaces that are made permanently to stationary monitors. In addition to the wiring cost to plug more devices on the network, there are severe incompatibility issues where each device manufacturer defines its own data link communication method. Therefore, proprietary drivers have to be loaded every time a different device is plugged into the network, making it unrealistic to plug in mobile devices several times during the day. In this context, there is a need for a universal and wireless interface that provides connectivity, untethered access to information, and replaces the "hard-wired" approach. This is even more complicated in military medical facilities that have to be deployed quickly near operational theaters with little time to configure and setup. Closing the gap on the network connectivity and scalability issues affecting the medical environment is poised to become a major effort in modernizing the current healthcare system for hospitals and medical units supporting soldiers in the battlefield.

The IEEE 1073 working group is currently developing standard specifications for medical device communication focusing on wireless technologies that are adequate for the clinical domain and the patient's bedside. The main objective for this effort is to develop a universal and interoperable interface for medical equipments, that is (1) transparent to the end user, (2) easy to use, and (3) quickly (re)configured. The purpose of the group is not so much to develop new technologies, but to evaluate the suitability of currently available technologies in the medical space.

In this article, we consider the IEEE 802.15.4 standard [1] that is a likely candidate for low bit rate wireless personal area network (WPAN) applications, given the low bandwidth, low power requirement of most patient bedside devices. We evaluate the performance of a network consisting of several communicating devices near a patient's bedside and stress the performance trade-offs that exist. Our objectives are to answer a number of questions concerning the performance and operation of a WPAN in a medical environment, for example: How many WPAN systems can co-exist in a patient's room? What is the impact of interference on performance? The remainder of this article is organized as follows. The next section gives a brief overview of the IEEE 802.15.4 protocol specification. In the performance evaluations section we consider scenarios using select medical applications to obtain a baseline in an error free environment and then discuss the impact of interference from multiple WPANs and wireless local area network (WLAN) devices. In the final section, we offer some concluding remarks.

## 802.15.4 LOW-RATE WPAN

The use of various wireless technologies for military and medical applications already exists (e.g., WLAN) [2] for Internet access and file sharing). However as time and technology progress, so does the infiltration of wireless into other areas and medical applications.

Cable replacement for removing tethering devices and flexible configuration for mobile units appear to be good reasons for applying wireless technologies to medical applications.

We examine the new low rate IEEE Std. 802.15.4-2003 and its application to low rate medical applications.

The IEEE Std. 802.15.4 describes a very low rate wireless technology that is designed for communication among wireless devices within a short range of each other, using very low power (most likely battery operated), and with low data rate requirements.

The WPAN that is created when using this technology may be classified in one of two types: unslotted or slotted. For the unslotted WPAN all devices are considered peers with respect to one another and the entire wireless resource is available. For the slotted WPAN a structure is imposed on the wireless resource. Both structures are shown in Figure 1.

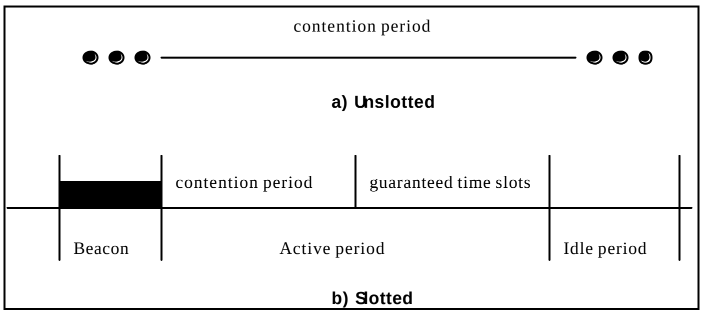


Figure 1. WPAN structures of wireless resource.

Within the slotted structure are potentially three time periods. The first is for the sending of the beacon frame. The two beacon frames bound this structure. The second is the period directly following the beacon frame. This second period may be considered the active portion of the structure because it is during this time period when transmission and receptions may occur. This second or active time period may be further divided into a contention period and a non-contention period. During the contention period all devices are considered peers and compete equally for the resource using a Carrier Sensed Multiple Access with Collision Avoidance (CSMA/CA) mechanism. During the non-contention period resources are allocated for use on a per device basis. The third period, if it exists, is an idle period when nothing is expected to be transmitted or received. This permits power savings while still maintaining synchronization with the beacon and a bound on delay.

As with most IEEE 802 standards, the 802.15.4 standard defines a physical layer and a medium access control (MAC) sublayer.

The physical layer defines three medium dependent wireless raw data rates covering three different frequency bands. These are 20, 40, and 250 kbit/s using the 868-868.6, 902-928, and 2400-2483.5 MHz frequency bands, respectively. In these respective frequency bands there are one, ten, and sixteen channels at these rates.

The MAC sublayer defines two CSMA/CA mechanisms, one for use in each of the two types of WPANs. Each have a number of default parameters that control the CSMA/CA process. For example the backoff exponent parameter bounds the range (from which a random value is selected) of the delay on how often an attempt is made to sense the wireless medium, and the maximum number of CSMA/CA backoffs parameter determines the number of attempts to sense the wireless medium for an idle condition before declaring a failure to transmit that particular frame.

We study only the unslotted WPAN when using the 2450 MHz band for a number of reasons. The 2450 MHz band provides the most channels (i.e., 16) at the highest data rates. The unslotted WPAN has the least overhead (i.e., no beacon frames). Based on the increased complexity for the slotted WPAN when compared to the unslotted WPAN, it is believed that the first devices available will have these characteristics.

## PERFORMANCE EVALUATIONS

We present simulation results to evaluate the performance of a low-rate WPAN in a healthcare environment. Our simulation environment is based on detailed MAC, PHY, and channel models for the IEEE 802.15.4 (low-rate WPAN). The channel model consists of a geometry-based propagation model for the signals, as well as a noise model based on Additive white Gaussian noise (AWGN). For the indoor channel, we apply a propagation model consisting of two parts: (1) line-of-sight propagation (free-space) for the first 8 meters, and (2) a propagation exponent of 3.3 for distances over 8 meters [3]. We develop models for the low-rate WPAN access protocols using the OPNET[1,2] network simulator and configure the applications available in the simulator library.

In general, we find that performance results vary according to the network configuration, usage scenario, and application considered [4]. First we show performance results when the default 802.15.4 MAC parameters are used for one WPAN to obtain a baseline. Second we show

[1] OPNET and OPNET Modeler are registered trademarks of OPNET Technologies, Inc.

[2] Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

the impact of interference on performance when another WPAN is present and when a WLAN is present.

**Baseline Results**

This experiment focuses on the scalability and the performance of the IEEE 802.15.4 technology in a multi-point to point topology (shown in Figure 2), where multiple transmitters are communicating with a single receiver.

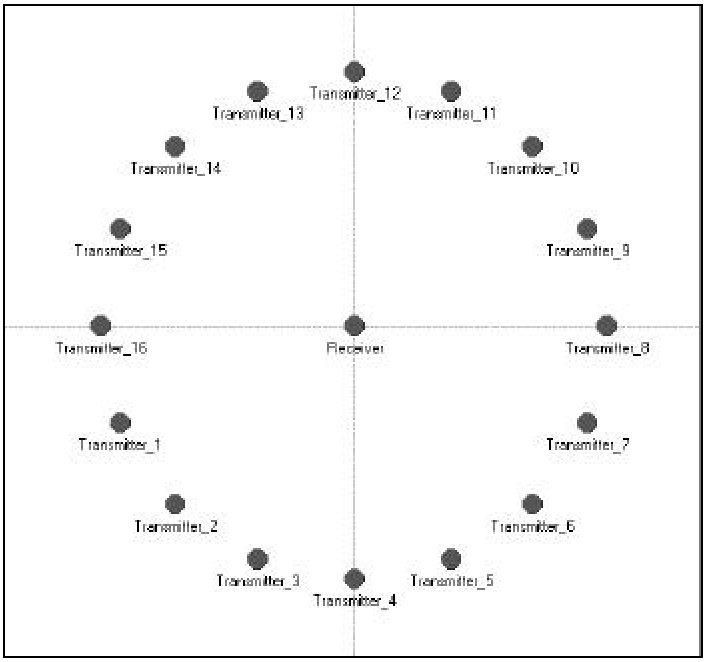


Figure 2. WPAN topology

For the WPAN, we consider a patient monitor consisting of an electrocardiograph (ECG) using multiple leads that produces a 1500 byte frame every 0.25 s [5], a blood analysis lead that produces a 1024 byte frame every second, a supervisory control that produces a 512 byte frame every second, and a 384 byte frame containing status or alert information every minute. The application parameters for the WPAN are shown in Table 1. The parameters used in the WPAN simulations are summarized in Table 2.

Table 1. Applications parameters used for WPAN.

| | Distribution | Value |
|---|---|---|
| Alarms & status,<br>Supervisory & control,<br>Blood analysis,<br>ECG | Constant | 384 byte / 60 s,<br>512 byte / s,<br>1024 byte / s,<br>1500 byte / 0.25 s |

The performance metrics used include the MAC sublayer access delay, the percentage of packets dropped at the transmitter's application layer, and the percentage of packets dropped at the MAC layer's receiver node. In addition, a goodput measure is computed as the number of successful packets received at the receiver's application layer divided by the available capacity (in number of application layer packets that could be transmitted over the medium). Each data point collected is averaged over 10 simulation trials using a different random seed for each trial. In addition to the mean value, we verify that the statistical variation around the mean values are small and fall within a 95% confidence interval.

Table 2. Simulation parameters used for WPAN.

| | Value |
|---|---|
| Length of simulation run (s) | 600 |
| Transmitted power (mW) | 1 |
| Packet header (bit) | 72 |
| Minimum backoff exponent | 3 (default) |
| Maximum number of backoffs | 4 (default) |

From Figure 3 we see that the packet delays are well within the medical requirements (i.e., < 500 ms) for delay, if this WPAN segment is considered the entire network. However, for the 1500 byte application this is deceiving, since the delay goes down as more transmitters are added. This is due to the way the application's data is sent and how the delay is calculated. Since the 1500 byte packet is too large for a single IEEE 802.15.4 MAC frame, multiple MAC frames (i.e., 16) are generated for each 1500 byte packet. All of these MAC frames are then queued, but once an error occurs in the transmission of one MAC frame (due to timeout or maximum retransmission attempts), then the remaining MAC frames are deleted from the queue as well.

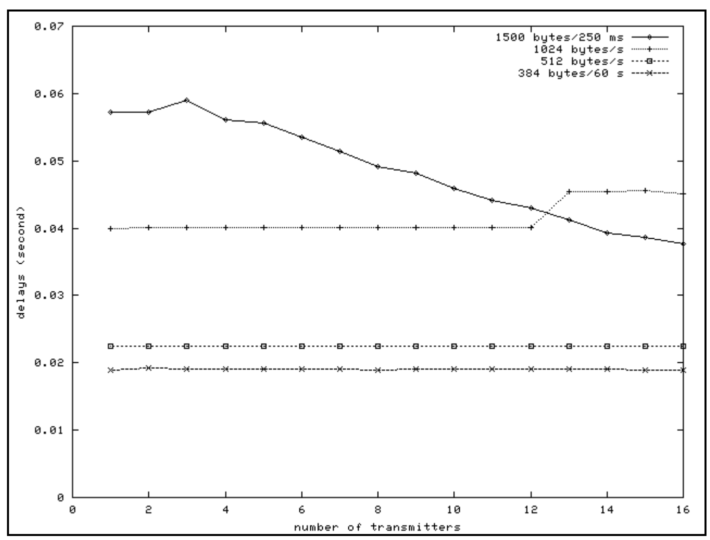


Figure 3. MAC sublayer access delay as a function of the number of transmitters.

From Figure 4 the effect of this is a dramatic decrease in goodput. The offered load on the WPAN reaches its maximum with just two devices. Adding just one more transmitter results in an overload of the WPAN's capacity. Due to the CSMA/CA mechanism when at least one of the MAC frames composing the application packet is lost, this results in an overall lower delay and goodput.

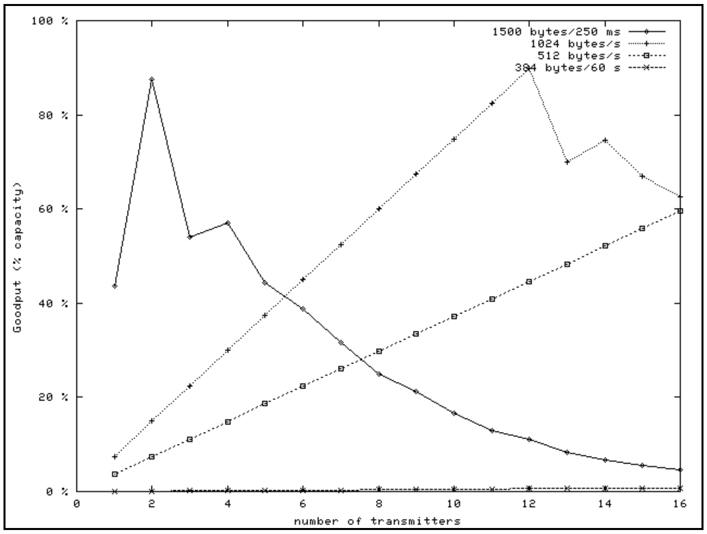


Figure 4. Goodput as a function of the number of transmitters

Figure 5 shows the MAC sublayer packet loss at the receiver, while Figure 6 shows the packet loss as seen by the application at the transmitter. The difference in these two perspectives shows the likelihood that an application packet will be lost due to a loss of a single MAC frame in the attempt to access the wireless resource versus the likelihood to lose a MAC frame due to interference of another transmitter (i.e., collision). For the 1500 byte application (ECG) the bit error rate (BER) is unacceptable for three or more transmitters. For the 1024 byte application it takes thirteen transmitters to have an unacceptable BER. The other applications are not shown, since the number of transmitters studied is not large enough to produce enough load to cause packet loss.

## Impact of Interference on Performance

Since it is highly unlikely that a WPAN using the 802.15.4 will be in an interference free environment, we study the effects of interference generated by multiple WPANs and by WLAN devices. First we cover the WPAN on WPAN interference. Secondly we cover the effects of interference in a mixed WLAN and WPAN environment.

For WPAN the application and simulation parameters are the same as those used in the previous section to obtain the baseline results.

*1) Impact of WPAN on WPAN Interference*

For the case of the interference caused by other 802.15.4 WPANs, most can be avoided by selecting one of the 16 channels that does not already contain a WPAN. This channel selection may be accomplished through manual configuration or by implementing optional dynamic procedures. However in order to investigate this type of interference, we assume the worst possible scenario, where two 802.15.4 WPANs (one for each patient) are located in a single hospital room and each WPAN uses the same channel. Each WPAN consists of a monitor with the four medical applications described and used in the previous section for baseline results. This topology is shown in Figure 7. We assume that there are two monitors 1 meter apart. Each monitor is about 25 cm away from a patient's bed, that is 150 cm wide.

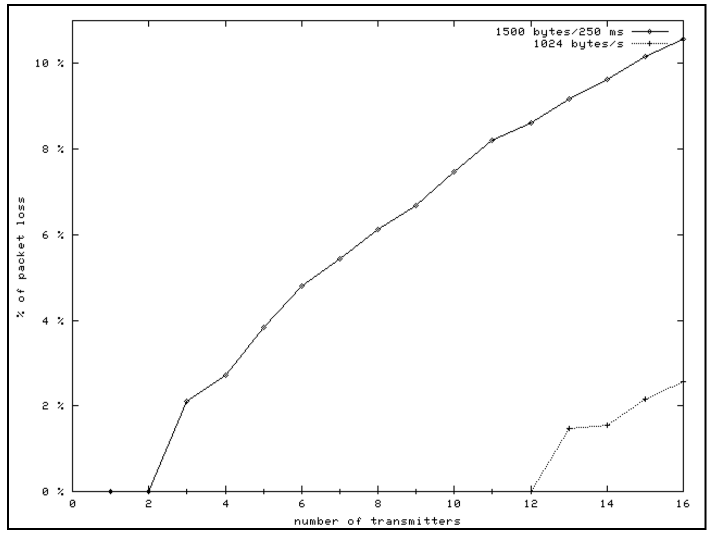


Figure 5. Percent of MAC frames lost at the receiver as a function of the number of transmitters

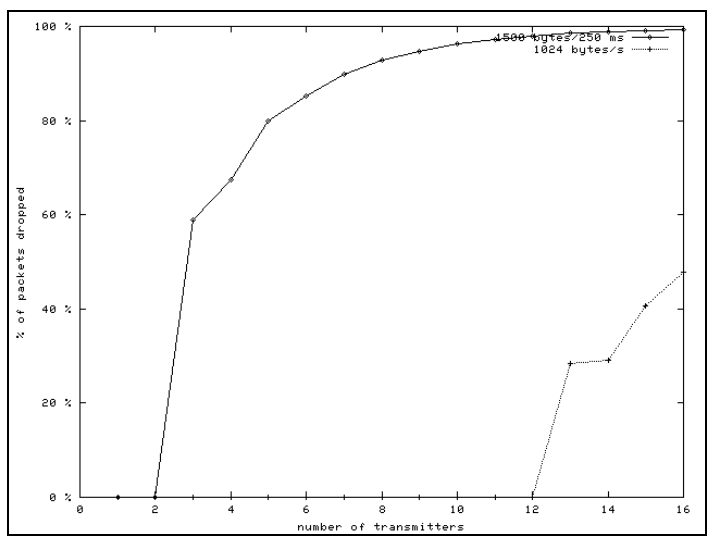


Figure 6. Percent of application packets dropped at the transmitter as a function of the number of transmitters

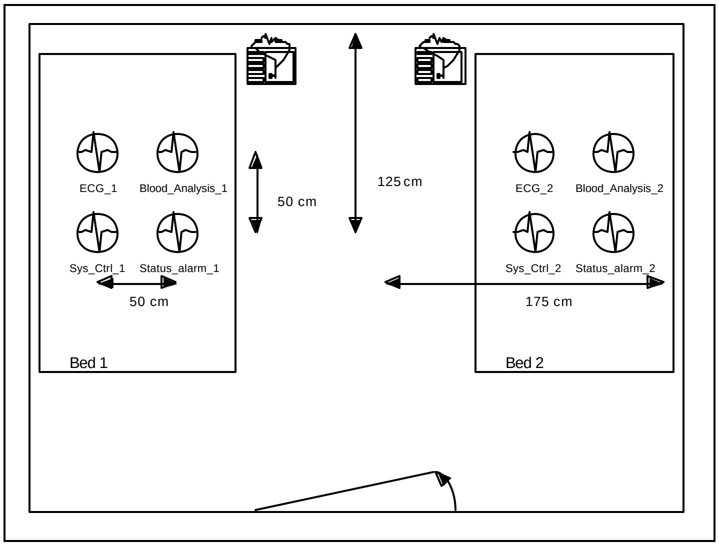


Figure 7. Hospital room WPAN topology

The packet loss, delay, and goodput from these experiments as seen by the monitors are shown in Table 3. There is a 69% goodput per WPAN system and an 18% packet loss observed at each monitor. Thus, the impact of WPAN on WPAN interference may be significant. The packet loss observed is comparable to the one obtained if all transmitters were connected to a single monitor. In this case, the solution is to configure each WPAN system to use a different channel, if available.

Table 3. Performance results of WPAN on WPAN interference

| | Packet loss (%) | Delay (s) | Goodput (%) |
|---|---|---|---|
| Monitor 1 | 18.10 | 0.0391 | 69.77 |
| Monitor 2 | 18.07 | 0.0392 | 69.99 |

*2) Impact of WLAN Interference on WPAN*

Since it is highly likely that a WLAN will exist in the same coverage space as a WPAN, it is important to assess the effect of interference caused by a WLAN on a WPAN and vice versa. This likelihood is assumed since the 802.15.4 wireless technology alone will not provide the necessary bandwidth for all medical applications in such an environment. In [6] we show the performance of the WPAN in an interference free environment, which allowed us to closely examine the packet loss, delay, and goodput when achieved in the best possible environment and under parameter manipulation. In contrast to [6] these experiments use only the default 802.15.4 parameters with the interference caused by a nearby WLAN.

For the WLAN the simulation and application parameters are given in Table 4 and Table 5. Four WLAN applications are simulated. A file of size 960 Mbytes is transferred using the file transfer protocol (FTP). Browsing an internet web site is simulated using Hyper Text Transfer Protocol (HTTP). Reading and writing electronic mail (e-mail) via the WLAN is simulated. A video stream is simulated at a constant rate and frame size.

Table 4. Simulation parameters used for WLAN

| | Value |
|---|---|
| Length of simulation run (s) | 600 |
| Transmitted power (mW) | 25 |
| Packet header (bit) | 224 |
| Packet payload | 12,000 |

Table 5. Applications parameters used for WLAN

| | Distribution | Value |
|---|---|---|
| **WLAN FTP** | | |
| File size (Mbyte) | Constant | 960 |
| **WLAN HTTP** | | |
| Page interarrival time (s) | Exponential | 5 |
| Number of objects per page | Constant | 2 |
| Object 1 size (byte) | Constant | 10K |
| Object 2 size (byte) | Uniform | [200K , 600K] |
| **WLAN E-mail** | | |
| Send interarrival time (s) | Exponential | 120 |
| Send group | Constant | 3 |
| Receive interarrival time (s) | Exponential | 60 |
| Receive group | Constant | 3 |
| E-mail size (byte) | Exponential | 1,024 |
| **WLAN video** | | |
| Frame rate (frame/s) | Constant | 1 |
| Frame size (byte) | Constant | 17,280 |

The 802.15.4 wireless technology, like the WLAN wireless technology, contains optional sensing methods for determining the idle or busy condition of the wireless resource. In the first set of experiments the optional sensing method used is for the detection of only frames that conform to 802.15.4. In the second set of experiments the optional sensing method is for the detection of any type of packet (i.e., WPAN and WLAN). Figure 8 shows the topology used for the WLAN and WPAN interference experiments. A WLAN server is placed 4 meters away from a WLAN station that is 1 meter apart from a WPAN receiver. The distance between the WPAN receiver and transmitter is set to 1 meter.

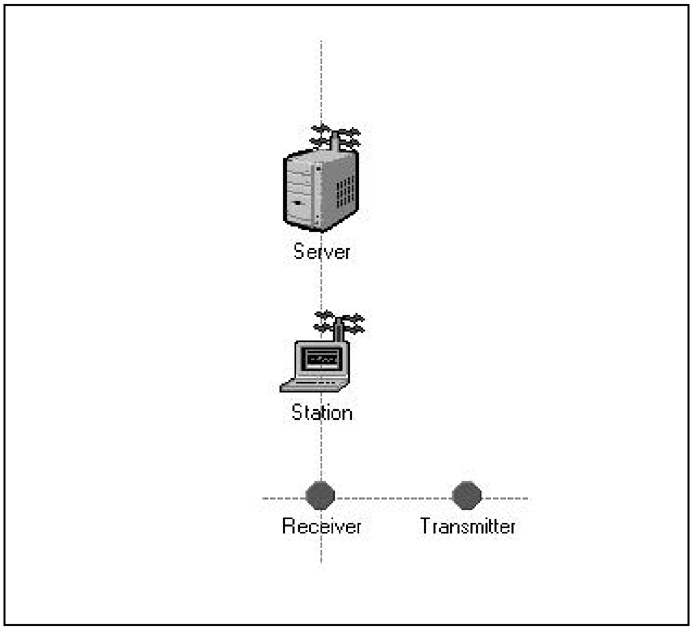


Figure 8. WLAN and WPAN topology

The results of these two experiments are shown in two sets of tables, Table 6 and Table 7, each consisting of four results: a) packet loss, b) MAC sublayer access delay, c) goodput, and d) WLAN station packet loss.

Considering the experiment with one WPAN and one WLAN when the WPAN only detects packets of its own type, one can see that the packet loss to the WPAN is significant, especially when the WLAN is transmitting video (see table 6a). The WLAN FTP and video applications have the most detrimental effect, since these applications occupy the wireless resource most of the time. For video, the WPAN packet loss is 100%, or nearly so, for all WPAN applications. For WLAN FTP the packet loss increases as the WPAN applications decrease in output from a packet loss of 13.9% for WPAN ECG to a packet loss of 90.7% for WPAN Alarm and Status. This latter data point is significant in that the likelihood of an alarm indication not reaching its destination is so high that one should not use this technology under these circumstances. The delays are bounded by the CSMA/CA and retransmission built-in functions and procedures.

The results are slightly different when the WPAN carrier sense can also detect the transmission of WLAN packets. In this case, the WPAN packet loss is lower for almost all of the WPAN applications as is shown in Table 7a. The few exceptions are when the WLAN is sending FTP traffic. Since the WPAN is now sensing for WLAN signals, most of its data is lost to the clear channel assessment (CCA) failing to find the medium idle. With the small amount of data to send for the Alarm and Status application, some of it gets sent without colliding. However, there are no successful WPAN packets received or 100% of packet loss for the WLAN video application and the WPAN alarm application. Note that if no packets are received correctly, the goodput is zero and the access delay calculation is not applicable (N/A). Finally from Table 7d, we note that the WLAN station packet loss is negligible when the WPAN is able to detect a WLAN transmission and thus allows the WLAN to get unlimited access to the medium. This provides a preferential treatment to the WLAN traffic.

Tables for Detection of the WPAN packets only

Table 6a. WPAN packet loss (%)

| | WLAN FTP | WLAN HTTP | WLAN Email | WLAN Video |
|---|---|---|---|---|
| WPAN ECG | 13.9 | 9.6 | 0.06 | 100 |
| WPAN Blood Analysis | 55.1 | 11.7 | 0.3 | 99.75 |
| WPAN Supervisory | 69.0 | 20.1 | 0.4 | 99.75 |
| WPAN Alarm Status | 90.7 | 38.6 | 8.1 | 100 |

Table 6b. WPAN MAC sublayer access delay (s)

| | WLAN FTP | WLAN HTTP | WLAN Email | WLAN Video |
|---|---|---|---|---|
| WPAN ECG | 0.058 | 0.058 | 0.057 | N/A |
| WPAN Blood Analysis | 0.044 | 0.040 | 0.040 | 0.029 |
| WPAN Supervisory | 0.029 | 0.024 | 0.022 | 0.029 |
| WPAN Alarm Status | 0.029 | 0.022 | 0.019 | N/A |

Table 6c. WPAN goodput (%)

| | WLAN FTP | WLAN HTTP | WLAN Email | WLAN Video |
|---|---|---|---|---|
| WPAN ECG | 68.0 | 77 | 99.75 | 0 |
| WPAN Blood Analysis | 25 | 78.2 | 99.3 | 0 |
| WPAN Supervisory | 21 | 79.2 | 99.3 | 0 |
| WPAN Alarm Status | 0 | 60 | 90 | 0 |

Table 6d WLAN station packet loss (%)

| | WLAN FTP | WLAN HTTP | WLAN Email | WLAN Video |
|---|---|---|---|---|
| WPAN ECG | 3.7 | 10.7 | 8.2 | 2.8 |
| WPAN Blood Analysis | 1.6 | 3.1 | 10.7 | 19.1 |
| WPAN Supervisory | 1.6 | 3.1 | 3.8 | 19.1 |
| WPAN Alarm Status | 1.0 | 1.0 | 2.0 | 2.7 |

Tables for WPAN Detection of all packets

Table 7a. WPAN packet loss (%)

| | WLAN FTP | WLAN HTTP | WLAN Email | WLAN Video |
|---|---|---|---|---|
| WPAN ECG | 45.5 | 3.5 | 0.07 | 81.9 |
| WPAN Blood Analysis | 74.0 | 3.8 | 0.09 | 52.3 |
| WPAN Supervisory | 76.7 | 7.0 | 0.30 | 68.9 |
| WPAN Alarm Status | 76.9 | 18.2 | 5.66 | 100 |

Table 7b. WPAN MAC sublayer access delay (s)

| | WLAN FTP | WLAN HTTP | WLAN Email | WLAN Video |
|---|---|---|---|---|
| WPAN ECG | 0.066 | 0.058 | 0.057 | 0.076 |
| WPAN Blood Analysis | 0.061 | 0.041 | 0.040 | 0.094 |
| WPAN Supervisory | 0.044 | 0.024 | 0.023 | 0.075 |
| WPAN Alarm Status | 0.028 | 0.022 | 0.024 | N/A |

Table 7c. WPAN goodput (%)

| | WLAN FTP | WLAN HTTP | WLAN Email | WLAN Video |
|---|---|---|---|---|
| WPAN ECG | 10.6 | 78.9 | 99.9 | 0.1 |
| WPAN Blood Analysis | 4.3 | 81.7 | 100 | 8.3 |
| WPAN Supervisory | 6.7 | 83.7 | 99.8 | 7 |
| WPAN Alarm Status | 10 | 70 | 100 | 0 |

Table 7d. WLAN station packet loss (%)

| | WLAN FTP | WLAN HTTP | WLAN Email | WLAN Video |
|---|---|---|---|---|
| WPAN ECG | 1.9 | 3.6 | 10.2 | 2.4 |
| WPAN Blood Analysis | 1.2 | 1.6 | 4.2 | 7.6 |
| WPAN Supervisory | 1.2 | 1.7 | 7.2 | 7.2 |
| WPAN Alarm Status | 1.1 | 1.1 | 2.4 | 2.4 |

## CONCLUDING REMARKS

In this article we investigate the use of the IEEE 802.15.4 standard specifications for medical applications in interference causing environments. Our findings can be summarized as follows.

We show that a WPAN sharing the same channel with another WPAN has no more interference effect than if all devices were using the same WPAN. However WLAN interference is detrimental to a WPAN using 802.15.4. It is envisioned that if the penetration of WLAN continues at its current rate, then a WPAN using 802.15.4 will be incapacitated, unless the WLAN is idle most of the time or on a different channel. Choosing the optional sensing mechanism that detects any packet type for the 802.15.4 WPAN will improve its performance, but perhaps not enough to make a difference.

## AKNOWLEDGEMENTS

We wish to acknowledge the members of the IEEE 1073, especially Jan Wittenber, developing the technical report on RF wireless for medical devices. Without their help we would not have current medical application information.

## REFERENCES

[1] IEEE Std. 802.15.4 – 2003, Standard for Telecommunications and Information Exchange Between Systems – Local Area Metropolitan Area Networks – Specific Requirements - Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPAN).

[2] IEEE Std. 802-11, IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification, June 1999.

[3] A. Kamerman and N. Erkocevic, "Microwave oven interference on wireless LANs operating in the 2.4 GHz ISM band," Proceedings of the 8th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, Vol.3, pp.1221-1227, 1997.

[4] N. Golmie, R.E. Van Dyck, A. Soltanian, A. Tonnerre, and O. Rebala, "Interference Evaluation of Bluetooth and IEEE 802.11b Systems," ACM Wireless Network, WINET, Vol. 9, pp. 200-211, May 2003.

[5] S. M.S. Jalaleddine, C. G. Hutchens, R. D. Strattan, W.A. Coberly, "ECG Data Compression Techniques – A Unified Approach," IEEE transactions on biomedical Engineering, Vol. 37, No. 4, April 1990.

[6] N. Golmie, D. Cypher, O. Rebala, "Performance Analysis of Low Rate Wireless Technologies For Medical Applications," to appear in Elsevier Computer and Communication Journal special issue on Performance Issues of Wireless LANs, PANs, and Ad Hoc Networks.