MEDICAL DEVICE DESIGN FROM A TELECOMMUNICATIONS PERSPECTIVE

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INTRODUCTION

The telecommunications industry has been challenged by the commercial sector to produce devices that are small in size, in expensive and that have a long battery life. Safety standards have also restricted frequency bands and transmission power. These requirements have resulted in an extremely demanding environment for product development, pushing the boundaries of innovation.

Breakthroughs in the medical profession have resulted in an increasing number of monitoring and diagnostic tools which are in demand from patients and health care workers. The trend in medical devices is improved performance in smaller, less expensive and mobile devices. These requirements have been core aspects of the telecommunications industry. It is therefore anticipated that medical-telecom cross disciplinary collaboration could inspire the next generation of medical devices. These collaborations are attractive as they will lead to scientific advancements in technologies as well as the improved diagnostics and treatments in health care. [1].

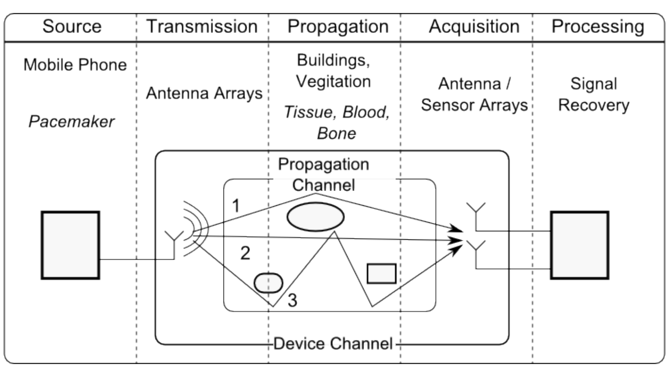

Figure 1: Medical / telecom system block diagram showing spatial and temporal multipath.

This paper compares two aspects of medicine and telecommunications: 1. the propagation channel and 2. signal acquisition needed to recover the information. In the telecommunications environment the source is a mobile phone which sends its signal through free space populated by scatterers. The signal is acquired by the receiver antennas. Analogously in the medical scenario, a part of the body or a device in the body is the signal source which transmits its information through the body's tissues. The signal is picked up by exterior antennas or sensors. In the last section, we consider diagnostic information collected by an intelligent pacemaker as an example. Figure 1 gives block diagram of the source-receiver path.

Selected telecommunications techniques will be explained and related to the pacemaker application. The intention is to stimulate a discussion between the telecommunications and medical communities.

MODELING THE SIGNAL ENVIRONMENT

In 1948, the information theory pioneer C. Shannon gave a mathematical upper bound to the amount of information that can be transmitted through a noisy signalling environment or channel. His theory did not describe a method to achieve this bound. However any successful medical or telecommunication transmission scheme depends on knowledge of the channel environment. An accurate model is necessary for the development of signal processing techniques, and in improving the accuracy of simulation.

Channel Definition

A channel can be described heuristically as the part of a system that cannot be controlled by the user. For a telecommunications channel this includes buildings, vegetation and the behaviour of other mobile phones. Bone, fat and other tissues would constitute the typical medical channel which would vary depending on the patient and the organ. Where the channel definition becomes ambiguous is at the boundary of the propagation environment and the device. The antenna or sensor used to send or collect the signal has an impact on the channel behaviour yet can also be designed by the user.

The system block diagram in Figure 1 shows two channel definitions. The inner channel is termed the *propagation channel.* It starts where the signal leaves the transmitter, includes the medium and any artefacts that affects the propagation and ends before the signal enters the receiver. Channel sounding techniques in telecommunications have minimized transmitter and receiver effects such as mutual coupling [2]. The 'Spatial Channel Model' used to evaluate 4th generation systems is one successful example of a propagation channel model used to test and standardize mobile phones [3]. The research area of Wireless Body Area Networks has begun to apply telecommunications techniques to signal transmission on, through and in the body [4].

The *device channel* includes the effects of the transmitter and receiver on the propagation channel as illustrated in Figure 1. Effects such as mutual coupling among antenna / sensor elements, and their electrical properties are included. The device channel is easier to obtain but its application is restricted to the type of device used to obtain the signal.

Spatial and Temporal Multipath

When a signal leaves the transmitter, its interaction with the environment distributes the power both temporally and spatially resulting in *multipath*. Figure 1 shows a multipath environment with three paths having different spatial and temporal properties.

Temporal multipath arises from the different propagation time of the paths from the transmitter to the receiver. Figure 2a gives an example of a temporal multipath as a function of time based on the paths in Figure 1. Spatial multipath is a result of diffraction and reflection of a signal which distributes it in space. Figure 2b shows a spatial representation of the received power as a function of angle for the illustrative case shown in Figure 1.

Information about spatial and temporal multipath is essential for signal recovery at the receiver as will be discussed in the Section *Signal Acquisition.*

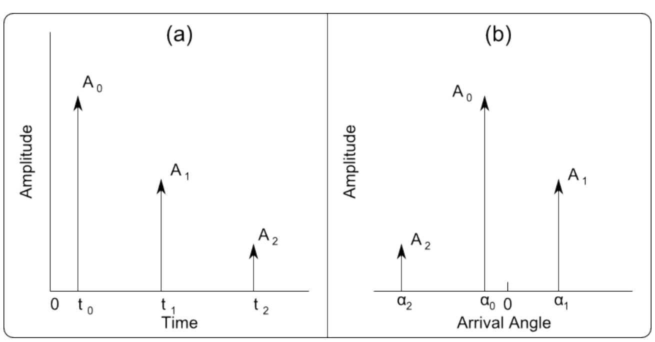

Figure 2: a) Temporal multipath, b) Spatial multipath

Noise and Interference

In addition to multipath, the signal is further corrupted by noise and interference. Noise is associated with random unwanted energy occupying the same channel resources as the desired signal. Additive White Gaussian Noise (AWGN) caused by thermal radiation is the dominant noise source in telecommunications and also plays a role in biomedical applications. For medical equipment 60 Hz noise from power lines is a major source of biomedical noise [5]. Knowledge of noise statistics allows receivers to be optimized for signal recovery as in [6].

Interference is similar to noise in that it is energy which overlaps the signal in time and frequency. However it has similar characteristics to it. In telecommunications environments, transmission from other wireless devices is the major source of interference. For ECG measurements, it is interference from electromyographic signals [7]. Knowledge of the interfering signal's properties allows the receiver to mitigate or remove the interference.

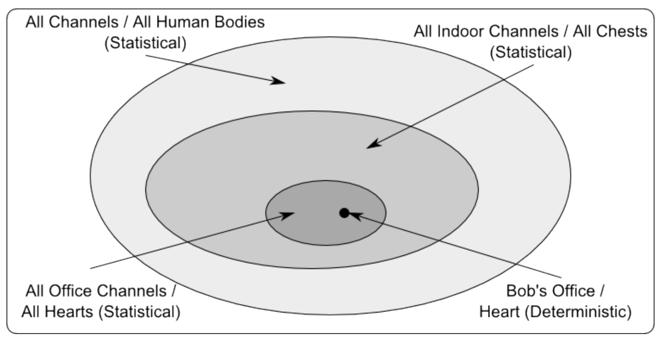

Figure 3: Continuum from a general statistical model to a specific deterministic model.

Deterministic and Statistical Channels

In the telecommunications literature, there are two distinct methods of channel modeling: *deterministic* and *statistical*. Deterministic models assume that all variables in the propagation environment are known. Detailed channel models are developed based on ray tracing or finite element calculations [8]. These models give an extremely high degree of predictability especially because antennas / sensors are modeled as part of the propagation channel. Deterministic channels are limited to a specific propagation geometry and are computationally complex. Deterministic telecommunications models are used in base station design where the device static in location.

The statistical model can be considered an ensemble of channel environments, each with an associated probability of occurrence. A statistical model can be constructed empirically by measuring multipath and noise parameters over a large number of transmission environments. The measurements are fit to statistical distributions to construct the models. Statistical models lack the detail of deterministic models; however they are computationally less intense, and can describe a range of propagation environments. The statistical model is used in mobile scenarios where the channel geometry cannot be known. The *Spatial Channel Model* [3] adopted for the 4th generation mobile standard consists of spatial and temporal distributions defined by a variety of environments such as rural and urban.

Channel Diversity

Spatial and temporal multipath has the disadvantage of making the collection of the desired signal power at the receiver more difficult. However, it also offers an advantage in terms of channel diversity.

Diversity is defined as the number of statistically independent paths containing the same information. Figure 4 plots the random temporal attenuation of two spatially uncorrelated paths. The probability that both signals are below a certain threshold is much smaller than that for a single channel. By definition, diversity is only relevant for statistical channel models.

Diversity is a property of the channel, and may be present in the time, frequency or spatial description of the signal. Recently, the telecommunications community has focused on exploiting spatial diversity through the use of multiple antennas and 4th generation mobile phones will benefit from it.

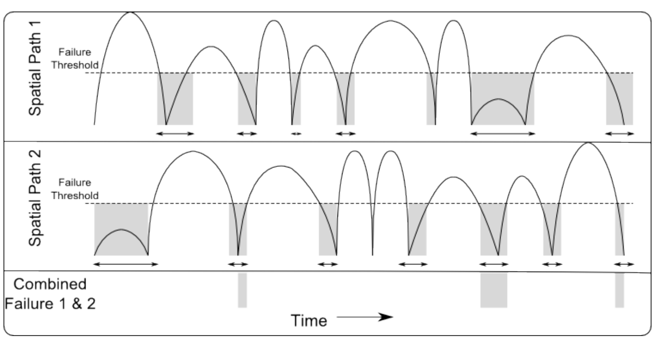

Figure 4: Illustration of diversity gain. Failure is higher for statistically independent spatial paths 1 and 2 when considered individually as opposed to combined.

SIGNAL ACQUISITION

The description of the received signal contains the required information necessary to recover the desired signal from the channel. The transmitter and/or receiver must first perform a *channel estimation* to find out the parameters needed for signal recovery.

Channel Estimation Techniques

Pilot symbol transmission is a straight forward method of channel estimation. A signal which is known at the receiver is sent over the channel. By convolving the received signal with the known pilot symbols, the receiver can estimate the propagation time t_i and direction α_i of the multipath components [9]. Pilot estimation techniques are simple however they waste resources. This is because the pilot symbols contain no information generated by the source. In medical applications, it may be difficult to send pilot symbols in the body. In [10], a form of pilot symbol channel estimation measured the fluid in a lung. This was done by sending a known acoustic signal through the mouth into the lungs. An array of electronic stethoscopes collected the signal for processing.

Blind channel estimation is more efficient in terms of transmission resources, however it is more computationally complex. Blind estimation exploits the known statistical properties of the signal of interest or by using decision feedback techniques [9]. Blind estimation may be suited to medical applications where the signal of interest has known characteristics. For example, the periodicity of resting heart signals could be used for blind channel estimation.

Temporal RAKE Receiver

Assuming that the channel estimation recovers the temporal parameters t_i, a RAKE receiver can be constructed to combine the different multipath components [9]. The receiver works by delaying the different temporal multipath components so they can be recombined. The RAKE receiver naturally exploits the temporal diversity of the channel. A block diagram of the RAKE receiver is shown in Figure 5a).

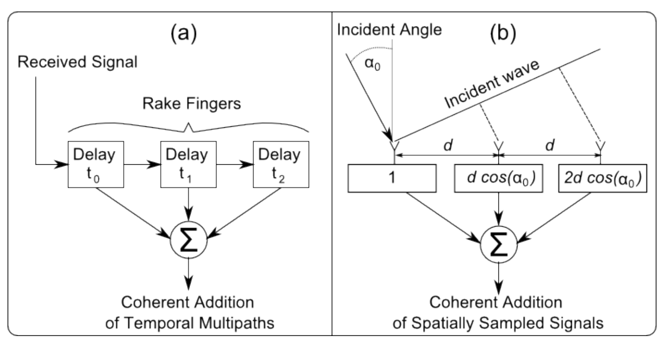

Figure 5: a) Block diagram of a RAKE receiver. b) Block diagram of a phased array.

Spatial Beamforming Phase Arrays

Antennas are devices which sample a signal in space, much the same way as a RAKE receiver samples in time [11]. Figure 5b) shows how a plane wave impinging on an antenna array results in different delayed versions of the same signal. Knowing the antenna geometry and the angle of arrival of the plane wave allows the receiver to combine the signal coherently in space. By increasing the number of antenna elements two approaches are possible. All the elements could focus on a single receiver direction. This would result in a narrow beam with a high gain, and would exclude noise or interference from other directions. Alternately, the antenna element phases could be calculated to combine signals coming from more than one spatial direction. This allows independent paths to be combined, which takes advantage of the spatial diversity of the channel.

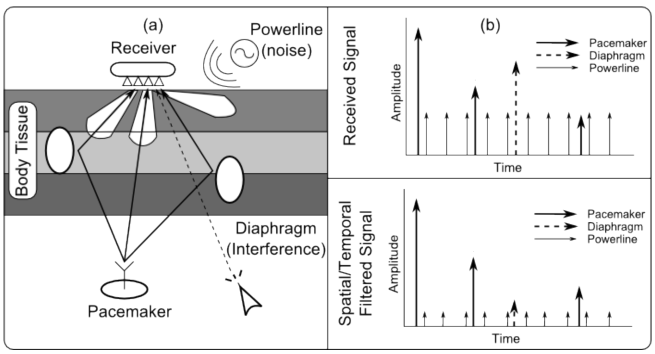

Figure 6: a) Smart pacemaker communicating to external receiver. b) Effect of spatial/temporal filtering.

MEDICAL APPLICATION: SMART PACEMAKER

An advanced pacemaker could perform diagnostic monitoring of the heart as well as its own functionality and battery life. The information would then need to be transmitted out of the body as shown in Figure 6.

The channel consists of bone, blood and tissue which result in three multipath components with different space and time parameters. The time-varying nature of the signal environment due to movement and biological functions makes this a statistical model. 60 Hz transmission line noise is generated from nearby equipment. In addition electromyographic interference is caused by signals from the diaphragm.

To estimate the channel, the pacemaker sends out pilot signals periodically which allow the external receiver to update the spatial and temporal parameters t_i and α_i. Blind channel estimation determines the spatial location of the diaphragm's interference based on its electrical signal characteristics.

Signal acquisition of channel multipath is done temporally by using the estimated path delays to coherently add the temporal multipaths using a RAKE receiver. A four element antenna array has three degrees of freedom. Two are used to form beams in the two largest signal directions. Noise is reduced temporally with a notch filter centred at 60 Hz to remove powerline noise. The final degree of spatial freedom constructs a spatial null in the direction of the diaphragm's signal. This is conceptually similar to notch filtering in frequency.

The output of the receiver is the desired signal. It combines the power of two independent multipath components. Channel diversity is also exploited due to the path independence. Electromyographic interference and powerline noise is reduced by spatial and temporal filtering as shown in Figure 6b.

CONCLUSION

This paper has introduced the telecommunications perspective of channel modeling and signal acquisition. It has identified several areas where this approach could be applied in the medical field and uses a smart pacemaker example to illustrate application of these concepts.

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