Spectrum Sharing Strategy for Radio Frequency-Based Medical Services

Ammar Ahmed, Shuimei Zhang, Vaishali S. Amin, Yimin D. Zhang

Advanced Signal Processing Laboratory, Temple University, Philadelphia, Pennsylvania, USA

{ammar.ahmed, shuimei.zhang, vamin, ydzhang}@temple.edu

Modern medical devices exploit radio frequency (RF) communication to remotely perform vital communication services for medical purposes. Real-time monitoring of health parameters, transferring of patient data to a data center or a cell phone, and controlling other medical devices are some of the important applications in medical science which exploit wireless communications. Some wireless devices also allow the mobility of patients or medical equipment on which these devices are mounted. Examples of such communication-enabled medical services are Wireless Medical Telemetry Service (WMTS) [1] and Medical Device Radiocommunications Service (MedRadio) [2].

The Federal Communications Commission (FCC) established the WMTS by allocating three wireless bands (608-614 MHz, 1395-1400 MHz, and 1427-1432 MHz) to Wireless Medical Telemetry Devices (WMTDs) where these devices can work as either primary or co-primary users. This spectrum allocation reduces the risk of electromagnetic interference between non-WMTDs and important medical telemetry signals [1]. However, the co-existence of several WMTDs within the same spectral band and close spatial vicinity remains challenging [2]. Due to the explosive growth in the number of WMTDs within limited hospital premises, their mutual interference may impede the efficient and reliable operation of these devices. FCC has also created MedRadio at ten different frequency bands for the operation of wireless Body Area Network (BAN) devices [2]. However, these devices are permitted only as secondary users in the 2360-2400 MHz band where the aeronautical telemetry holds the primary status. In the future, more complex BANs need to be designed in order to provide the computational functionalities required for high data rate applications [3]. Due to the significant increase in co-existing BAN devices and an unprecedented interest of medical community in their applications, spectrum sharing will become increasingly important.

Spectrum sharing enables the co-existence of several devices within the same spectral band. However, the existing strategies are originally developed for other applications and may not be directly suitable for accepted operation of the medical devices. Some of the important spectrum sharing techniques discussed in literature are multiple access [5-7], spatial multiplexing [5, 8-11], distributed multiple-input multiple-output (MIMO) [12], scheduling [13], and hybrid approaches [14, 15]. In state-of-the-art multiple access techniques [5], different devices operate in dedicated time or frequency slots, or exploit unique orthogonal waveform codes. However, these techniques do not ensure effective spectrum utilization and become complicated when the total number of operating devices changes over time, or when different devices have different communication requirements. Packet-based random access techniques like ALOHA and slotted ALOHA allow the access of communication resources randomly [3], but they have a low spectral efficiency in the presence of a large number of devices due to packet collisions. Such collision is avoided in carrier sense multiple access (CSMA) techniques where the devices sense the spectrum before transmitting [3]. CSMA has the promising performance; however, it only works if all the devices can hear each other and are equipped with spectrum sensing capabilities [3]. Scheduling [13] mitigates the interference; however, it allows the operation of only one device at a time. On the other hand, spatial multiplexing [8-11] is an advanced spectrum sharing strategy which employs antenna array beamforming to transmit different communication streams in different directions, but it is impractical for medical devices with a single or few antennas to form narrow beams that separate closely spaced devices. Distributed MIMO spectrum sharing systems [12] employ multiple orthogonal waveforms having the same spectral content to exchange the communication information. However, due to a large number of medical devices, it is extremely challenging to develop numerous orthogonal waveforms and ensure mutual orthogonality among their time delayed versions. Hybrid spectrum sharing approaches exploit directional antennas along with priority-based access to enable multi-beam communications [14, 15]; however, such approaches also require smart antenna arrays. Therefore, novel spectrum sharing strategies are required for efficient co-existence of RF capable medical devices.
We propose a novel spectrum sharing strategy for the co-existence of medical devices within the same spectral band and communication vicinity by employing orthogonal waveforms and scheduling simultaneously. The optimization problem is formulated in terms of the sum as well as the worst-case communication capacity.

Consider $N$ medical devices exploiting the same bandwidth resource with non-negligible mutual interference among them. Each device transmits data to a fusion center which is wirelessly visible to all the devices and only one device is activated at a time to transmit the information. If the $n$th medical device is activated, the corresponding Shannon capacity $C_n$ is expressed as:

$$C_n = B \log_2 \left(1 + \frac{p_n h_n}{\sigma^2_{\text{noise}}}ight), \quad n = 1, 2, \ldots, N,$$

where $B$ is the available signal bandwidth, $p_n$ and $\sigma^2_{\text{noise}}$ respectively denote the transmit power of the $n$th device and the noise power at the fusion center, and $h_n$ represents the channel power gain between the $n$th device and the fusion center. Since the operation of some medical devices can be more critical than the others, we express $C_{n,\text{min}}$ as the minimum required communication capacity for the $n$th medical device. The vectors containing the available capacity and the minimum required communication capacity for all the devices are expressed as $C = [C_1, C_2, \cdots, C_N]^T$ and $C_{\text{min}} = [C_{1,\text{min}}, C_{2,\text{min}}, \cdots, C_{N,\text{min}}]^T$, respectively, where $(\cdot)^T$ denotes the transpose operator. Spectrum sharing is enabled by employing $W$ orthogonal waveforms by each medical device such that each waveform exploits the same spectral bandwidth $B$. Let $T \in \mathbb{R}^{W \times N}$ be a matrix such that its $(w, n)$th element $t_{w,n}$ represents the activation time of the $n$th device using the $w$th waveform. We maximize the sum communication capacity of the system by exploiting the following convex optimization:

$$\max_T \quad 1^T_W T C$$
$$\text{s.t.} \quad T 1_N \leq 1^T_W T,$$
$$T^T 1_W \circ C \geq C_{\text{min}},$$
$$T \geq 0,$$

where $1_W$ and $1_N$ are the column vectors of all ones having the respective lengths of $W$ and $N$, $T$ denotes the maximum aggregate activation time of all the devices, $0$ is the $W \times N$ order matrix of all zeros, and $\circ$ represents the Hadamard product.

In order to enforce the communication interval to be a multiple of the packet duration $T_s$, we modify the above optimization as:

$$\max_T \quad 1^T_W T C$$
$$\text{s.t.} \quad \bar{T} 1_N \leq 1^T_W T / T_s,$$
$$T^T 1_W \circ C \geq C_{\text{min}} / T_s,$$
$$\bar{T} \geq 0,$$

such that $T = \bar{T} T_s$ and the $(w, n)$th element of $\bar{T}$ is $\bar{t}_{w,n} \in \mathbb{Z} \forall w, n$. The above optimization is a mixed-integer linear program (MILP) which is NP hard and can be solved by exploiting conventional MILP methods like branch and bound [16,17]. Such approaches are less computationally expensive than the conventional brute-force search [16].

When it is desirable to democratize the achieved communication capacity for each device, we can employ the worst-case optimization as follows:

$$\max_T \quad x$$
$$\text{s.t.} \quad \bar{T} 1_N \leq 1^T_W T / T_s,$$
$$T^T 1_W \circ C \geq x 1_N \geq C_{\text{min}} / T_s,$$
$$\bar{T} \geq 0,$$

where $x$ is the worst-case communication capacity. We use Gurobi solver [17] for solving all the optimizations. Simulation results illustrate the performance of the proposed strategies.
ACKNOWLEDGMENT

This work is supported in part by the National Science Foundation (NSF) under grant AST-1547420.

REFERENCES


ABSTRACT

We use Shannon's capacity as the optimization criterion for devising the spectrum sharing strategies. Consider \( N \) medical devices exploiting the same bandwidth resource with non-negligible mutual interference among them. Each device transmits data to a fusion center which is wirelessly visible to all the devices and only one device is activated at a time to transmit the information. If the \( n \)-th medical device is activated, the corresponding Shannon capacity \( C_n \) is expressed as:

\[
C_n = B \log_2 \left( 1 + \frac{P_n \alpha_n}{\sum_{m \neq n} P_m \alpha_m} \right), \quad n = 1, 2, \ldots, N,
\]

where:
- \( B \): Available signal bandwidth,
- \( P_n \): Transmit power of the \( n \)-th device,
- \( \alpha_n \): Noise power at the fusion center,
- \( \alpha_n \): Channel power gain between the \( n \)-th device and the fusion center.

OPTIMIZATION STRATEGIES

Spectrum sharing is enabled by employing waveform diversity and optimized scheduling. Important definitions are as follows:

\[
C_{\text{min}} = \left[ C_{\text{min1}} C_{\text{min2}} \cdots C_{\text{minN}} \right]: \text{Minimum required capacity for all the communicating devices},
\]

\[
W: \text{Total number of orthogonal waveforms shared by all devices},
\]

\[
T \in \mathbb{R}^{W \times N}: \text{Matrix of time instants such that its } (w, n)\text{th element } T_{nw}\text{ represents the activation time of } n\text{th device using } w\text{th waveform},
\]

\[
T: \text{Maximum aggregate activation time of all the devices.}
\]

Maximize the Sum Communication Capacity

We can maximize the sum communication capacity by exploiting the following linear program:

\[
\begin{align*}
\text{max} & \quad \sum_{n} T_n C_n \\
\text{s.t.} & \quad T_{nw} \leq T_n, \\
& \quad T_{nw} \leq C_{\text{min}}, \\
& \quad T_n \geq 0.
\end{align*}
\]

where \( \max \) and \( \min \) are Hadamard products.

In order to enforce the communication interval to be a multiple of the packet duration \( T_p \), we modify the above optimization as the following MILP:

\[
\begin{align*}
\text{max} & \quad \sum_{n} T_n C_n \\
\text{s.t.} & \quad T_{nw} \leq T_n, \\
& \quad T_{nw} \leq C_{\text{min}}, \\
& \quad T_n \geq 0, \\
& \quad T_n \text{ is integer multiple of all zeros},
\end{align*}
\]

SUM CAPACITY MAXIMIZATION

The corresponding achieved communication capacity for each device is illustrated in Fig. 3. Note that all the devices achieve the minimum required communication capacity; however, most of the communication capacity is achieved by the device 3 which has the most favorable channel conditions. Observe that the sum capacity maximization does not democratically achieve the communication capacity for each device.

REFERENCES


ACKNOWLEDGEMENT

This work is supported in part by the National Science Foundation (NSF) under grant AST-1547420.