Spectrum Sharing Strategy for Radio Frequency-Based Medical Services

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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 acceptable 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 nth medical device is activated, the corresponding Shannon capacity C_n is expressed as:

$$C_n = B \log_2 \left(1 + \frac{p_n h_n}{\sigma_{\text{noise}}^2}\right), \quad n = 1,2,\cdots,N, \tag{1}$$

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

$$\begin{aligned} \max_{\mathbf{T}} \quad & \mathbf{1}_W^{\mathrm{T}} \mathbf{T} \mathbf{C} \\ \text{s.t.} \quad & \mathbf{T} \mathbf{1}_N \leq \mathbf{1}_W T, \\ & \mathbf{T}^{\mathrm{T}} \mathbf{1}_W \circ \mathbf{C} \geq \mathbf{C}_{\min}, \\ & \mathbf{T} \geq \mathbf{0}, \end{aligned} \tag{2}$$

where $\mathbf{1}_W$ and $\mathbf{1}_N$ 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, $\mathbf{0}$ 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:

$$\begin{aligned} \max_{\bar{\mathbf{T}}} \quad & \mathbf{1}_W^{\mathrm{T}} \bar{\mathbf{T}} \mathbf{C} \\ \text{s.t.} \quad & \bar{\mathbf{T}} \mathbf{1}_N \leq \mathbf{1}_W \, T/T_{\mathrm{s}}, \\ & \left(\bar{\mathbf{T}}^{\mathrm{T}} \mathbf{1}_W\right) \circ \mathbf{C} \geq \mathbf{C}_{\min}/T_{\mathrm{s}}, \\ & \bar{\mathbf{T}} \geq \mathbf{0}, \end{aligned} \tag{3}$$

such that $\mathbf{T} = \bar{\mathbf{T}} T_{\mathrm{s}}$ and the (w,n)th element of $\bar{\mathbf{T}}$ 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:

$$\begin{aligned} \max_{\bar{\mathbf{T}}} \quad & x \\ \text{s.t.} \quad & \bar{\mathbf{T}} \mathbf{1}_N \leq \mathbf{1}_W \, T/T_{\mathrm{s}}, \\ & \left(\bar{\mathbf{T}}^{\mathrm{T}} \mathbf{1}_W\right) \circ \mathbf{C} \geq x \mathbf{1}_N \geq \mathbf{C}_{\min}/T_{\mathrm{s}}, \\ & \bar{\mathbf{T}} \geq \mathbf{0}, \end{aligned} \tag{4}$$

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.

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Abstract

- Modern medical devices exploit radio frequency (RF) communication to remotely perform vital communication services for medical purposes.
- Frequency bands allocated to medical devices are also shared by other applications resulting in mutual interference.
- Spectrum sharing enables the co-existence of several devices within the same spectral band; however, existing spectrum sharing strategies, originally developed for other applications, are not feasible for medical devices.
- A novel spectrum sharing strategy for medical services is presented which exploits waveform diversity and optimized scheduling.
- The optimization problem is formulated in terms of the sum as well as the worst-case communication capacity.
- The optimization strategy results in mixed-integer linear programs (MILPs). We exploit Gurobi Optimizer, which allows the solver integration with popular platforms like Python, C/C++ and MATLAB, to solve the MILPs.

Background

- Radio frequency spectrum is costly and limited. Therefore, the Federal Communications Commission (FCC) has no feasible choice but to allocate the same spectrum bands to multiple applications.
- FCC has created MedRadio at ten different frequency bands for the operation of wireless Body Area Network (BAN) devices; however, BAN devices can only work as secondary users in the presence of aeronautical telemetry service.
- FCC also established the Wireless Medical Telemetry Services (WMTS) by allocating three wireless bands (608-614 MHz, 1395-1400 MHz, and 1427-1432 MHz) to Wireless Medical Telemetry Devices (WMTDs) such that these devices either have a primary status, or a co-primary status where the primary radio astronomy users co-exist.
- Co-existence of multiple applications within same spectral bands emphasizes the importance of spectrum sharing.
- With ever-increasing interest in BAN and WMTDs, we see an explosive growth in the number of devices which further illustrates the importance of improved spectrum sharing strategies.

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Problem Formulation

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 nth medical device is activated, the corresponding Shannon capacity C_n is expressed as:

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

B: Available signal bandwidth,

p_n: Transmit power of the nth device,

σ^2_{noise}: Noise power at the fusion center,

h_n: Channel power gain between the nth device and the fusion center.

Optimization Strategies

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

$\mathbf{C}_{\min} = [C_{1,\min}, C_{2,\min}, \cdots, C_{N,\min}]^{\mathrm{T}}$: Minimum required capacity for all the communicating devices,

W: Total number of orthogonal waveforms shared by all devices,

$\mathbf{T} \in \mathbb{R}^{W\times N}$: Matrix of time instants such that its (w,n)th element $t_{w,n}$ represents the activation time of nth device using wth waveform,

T: 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:

$$\begin{aligned}\max_{\mathbf{T}}\ & \mathbf{1}_W^{\mathrm{T}}\mathbf{T}\mathbf{C} \\ \text{s.t.}\ & \mathbf{T}\mathbf{1}_N \le \mathbf{1}_W T, \\ & \mathbf{T}^{\mathrm{T}}\mathbf{1}_W \circ \mathbf{C} \ge \mathbf{C}_{\min}, \\ & \mathbf{T} \ge \mathbf{0},\end{aligned} \qquad \text{(P1)}$$

$\mathbf{1}_W$: $W\times 1$ column vector of all ones,

$\mathbf{1}_N$: $N\times 1$ column vector of all ones,

$\mathbf{0}$: $W\times N$ order matrix of all zeros,

$\circ$: 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 the following MILP:

$$\begin{aligned}\max_{\mathbf{T}}\ & \mathbf{1}_W^{\mathrm{T}}\bar{\mathbf{T}}\mathbf{C} \\ \text{s.t.}\ & \bar{\mathbf{T}}\mathbf{1}_N \le \mathbf{1}_W T/T_s, \\ & \bar{\mathbf{T}}^{\mathrm{T}}\mathbf{1}_W \circ \mathbf{C} \ge \mathbf{C}_{\min}/T_s, \\ & \bar{\mathbf{T}} \ge \mathbf{0},\end{aligned} \qquad \text{(P2)}$$

such that $\mathbf{T} = \bar{\mathbf{T}}T_s$ and (w,n)th element of $\bar{\mathbf{T}}$ is $\bar{t}_{w,n} \in \mathbb{Z}\ \forall w,n$.

Maximize the Worst-Case Communication Capacity

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

$$\begin{aligned}\max_{\mathbf{T}}\ & x \\ \text{s.t.}\ & \bar{\mathbf{T}}\mathbf{1}_N \le \mathbf{1}_W T/T_s, \\ & (\bar{\mathbf{T}}^{\mathrm{T}}\mathbf{1}_W) \circ \mathbf{C} \ge x\mathbf{1}_N \ge \mathbf{C}_{\min}/T_s, \\ & \bar{\mathbf{T}} \ge \mathbf{0},\end{aligned} \qquad \text{(P3)}$$

where x is the worst-case communication capacity.

Simulation Scenario

We consider $N = 4$ medical devices exploiting $W = 6$ orthogonal waveforms and a bandwidth $B = 1$ MHz such that the minimum communication capacity of $C_{n,\min} = 1$ Mbps ($\forall\, n$) is required for each device to transfer information to the fusion center. The optimization is performed for a time period of $T = 1$ msec whereas the packet duration is set to $T_s = 0.2$ msec. All the devices transmit with a power $p_n = 1$ mW. The channel conditions are expressed in Fig. 1.

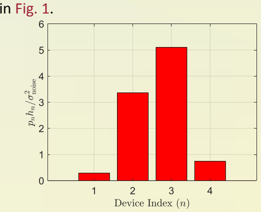

Fig. 1: Channel conditions of medical devices under consideration

Sum Capacity Maximization

The resource allocation achieved from the sum capacity maximization in MILP (P2) is illustrated in Fig. 2. It is observed that most of the time slots and waveform resources are allocated to device 3 which has the best channel conditions. This is to ensure that the sum communication capacity is maximized. Note that the activation times for all the devices are the integer multiples of packet duration.

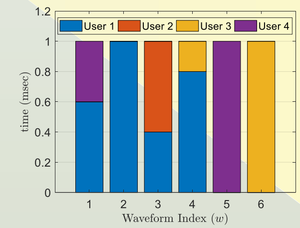

Fig. 2: Resource allocation for the devices using MILP (P2)

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.

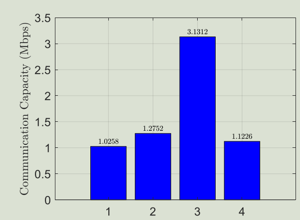

Fig. 3: Achieved communication capacity using MILP (P2)

Worst-Case Capacity Maximization

In some circumstances, it is desirable to achieve the same communication capacity for all the devices. In such a scenario, the communication capacity for each device can be democratically achieved by employing the worst-case optimization in MILP (P3).

Fig. 4 illustrates the resource allocation achieved by using MILP (P3). It can be observed that the devices with good channel conditions are allocated less resources than the devices with worse channel conditions. This strategy ensures that each device gets the same communication capacity. However, such a strategy should be used with caution because it can result in draining a lot of resources to the devices having the worst channel conditions, resulting in inferior system performance.

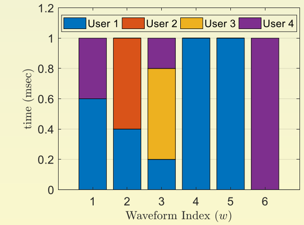

Fig. 4: Resource allocation for the devices using MILP (P3)

The corresponding achieved communication capacity for each device is illustrated in Fig. 5. Note that all the devices do not achieve exactly the same communication capacity. This is because the fractional time slots are not allowed, i.e. all the activation times are integer multiples of packet duration T_s.

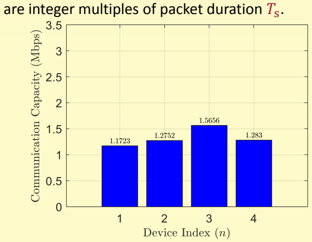

Fig. 5: Resource allocation for the devices using optimization (P3)

Conclusion

We proposed a novel spectrum sharing strategy for the co-existence of medical devices within the same spectral band and communication vicinity by simultaneously employing orthogonal waveforms and scheduling. The optimization problem is formulated in terms of the sum as well as the worst-case communication capacity. All the resulting optimizations take the form of mixed-integer linear programs which can be solved using the widely available tools like Gurobi, MOSEK and CPLEX. Simulation results illustrate the performance of the proposed approaches.

Acknowledgement

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