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# Instantaneous Frequency-division Multiplexing (IFDM): An Analog Multicarrier Approach to Wireless *In Vivo* Video

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***Abstract***- This work discusses the video signal processing and wireless communications portions of a biomedical virtually transparent epidermal imagery (VTEI) system for laparo-endoscopic single-site (LESS) surgery. VTEI uses a multitude of wireless micro-cameras that require high data-rate links. The prototype VTEI system also projects the generated panoramic view on the abdomen area to create a transparent display effect that mimics equivalent, but higher risk, open-cavity surgeries. For wireless communications, this paper discusses a theoretical wireless communication scheme for high-rate data links in situations that require extremely small-footprint image sensors and in zero-latency applications. In such situations the typical optimized metrics in communication schemes, such as power, are far less important than latency and hardware footprint that absolutely preclude their use if not satisfied. This work discusses the potential of a new multicarrier modulation technique, instantaneous frequency-division multiplexing (IFDM), where analog signals are frequency modulated and duplexed, occupying the same bandwidth, but are instantaneously separable and demodulated.

***Keywords:*** Multicarrier waveforms, Analog systems, Biomedical devices, High-definition video, Digital communications

## 1. Introduction

For many modern high data-rate applications, multicarrier modulation schemes are considered due to their high spectral efficiency and immunity to multipath distortion. Traditional multicarrier modulation schemes effectively utilize a filterbank to exploit the orthogonality of the multiplexed signals in the frequency domain (Proakis & Salehi 2008). The most common method, orthogonal frequency division multiplexing (OFDM) uses the discrete Fourier transform (DFT) (Goldsmith 2005) for modulation and demodulation; others have developed similar schemes using the modified DFT (MDFT) (Kai, Weiwei & Guangyu 2013), wavelet packet-based transforms (Xingxin, Mingquan & Zhenming 2002), and extended lapped transforms (Ohm, Schur & Speidel 2001). One weakness of multicarrier modulation schemes with large numbers of carriers is the peak-to-average power (PAPR) requirements as they impose on power amplifiers in the transmitter (Han & Lee 2005). High rate, multicarrier systems have application in all facets of wireless communications from modern cellular networks to body-area networks to biomedical devices.

One such application of a high rate system is in next-generation minimally invasive surgery (MIS). MIS - utilizing small incisions in the body for placement and manipulation of surgical equipment - has been widely adapted and performed as an alternative to certain open-cavity surgeries that increase trauma to the patient; however, MIS operations often take longer to complete than equivalent open-cavity operations, with associated patient risks to microbial contamination. The MIS procedure also poses challenges to skilled surgeons in many aspects: limited view and limited number of view points fixed by the insertion sites, an overhead monitor that displays the video from the videoscope but does not have a consistent and clear indication of orientation of the video. Extending from MIS is natural orifice transluminal endoscopic surgery (NOTES) or, similarly, laparo-endoscopic single site (LESS) surgery - recently developed MIS techniques - whereby "scarless" abdominal operations can be performed with multiple endoscopic tools passing through a natural body orifice, such as the umbilicus, as the insertion point. Though there are advances in MIS-related equipment (Artibani, Fracalanza, Cavalleri, Iafrate, Aragona, Novara, Gardiman & Ficarra 2008, Kaul, Laungani, Sarle, Stricker, Peabody, Littleton & Menon 2007, Hu, Allen, Hogle, & Fowler 2008, Rentschler, Dumpert, Platt, Farritor & Oleynikov 2007, Chen, Zhang, Zhang, Li, Qi, Jiang & Wang 2009, Dung & Wu 2010), including flexible tip endoscopes or robotic surgical platforms, surgeons often have to rely heavily on their experience to sense the locations of tools relative to the internal surgical area.

We are currently working on a virtually transparent epidermal imagery (VTEI) system (Sun, Anderson, Castro, Lin & Gitlin 2011, Castro, S., Smith, Alqassis, Ketterl, Sun, Ross, Rosemurgy, Savage & Gitlin 2012, Anderson, Lin & Sun 2013) as an enhancement to NOTES or LESS surgery, that will be composed of several micro wireless cameras to mitigate the bottleneck issue. In general, wireless video links, especially when high definition (HD), are considered high data-rate and are a prime candidate for multicarrier systems. These wireless image sensors are inserted at the beginning of the procedure and tethered to the inside of the abdomen. Tethering needles are also used to power the devices though newer versions of the sensors will be completely non-invasive (i.e. no additional puncture points). These video images from the wireless laparoscopes are transmitted wirelessly to some external receiver and then reprojected onto the abdomen of the patient (Fig. 1). This gives surgeons a disorientation-free view of the surgical area and lessens the dexterity issue of these advanced surgical procedures. A key consideration in making VTEI a reality is the wireless transmission of video images to the external system.

Traditionally the focus of digital wireless communications schemes, including real-time wireless HD video and multicarrier systems, has been to maximize the data rate over some bandwidth with the minimum amount of power necessary (Proakis & Salehi 2008). These metrics of power, rate, and bandwidth are at the heart of wireless communications since these are also primarily the scarce resources in the system. While this is true in most cases the current work studies a scenario where this traditional approach to optimized wireless links may not be as applicable as other system metrics such as in *in vivo* wireless biomedical devices.

*In vivo* biomedical devices are almost intrinsically wireless in nature due to the medium in which they reside - our own bodies. The approaches taken to establish a wireless link for data transfer with an *in vivo* device or sensor can take the form of different wireless methods. One such method uses various forms of induction in order to create a link between the device inside the body and the outside world (Ghovanloo & Najafi 2004, Wu, Li & Kao 2011, Mandal & Sarpeshkar 2008) which can also be applicable to power coupling or harvesting. Due to the highly absorptive nature of human tissue, the short transmission ranges, and low required data rates in some sensors, acoustic transmissions have also been proposed as a method to procure data (Shih & Shih 2010, Galluccio, Melodia, Palazzo & Santagati 2012). Finally, classical radio-frequency (RF) wireless links have been proposed for use in *in vivo* biomedical devices (Si, Hu, Malpas & Budgett 2008, Bashirullah 2010, Zhang, Feng, Geng, Yan & Wu 2011) that include their own strengths, often due to the maturity of the field, but also some weaknesses specifically from this unique wireless medium.

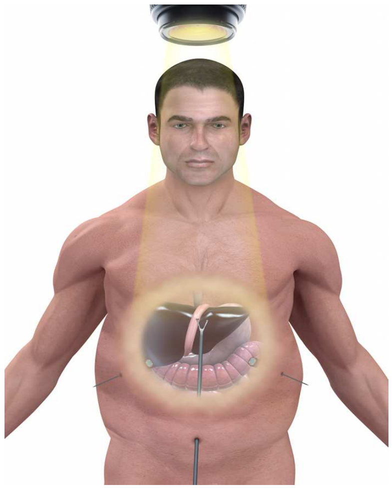

Fig. 1. A visual representation of the virtually transparent epidermal imagery (VTEI) system. Implanted wireless camera images are reprojected onto the patient to give the impression of open cavity viewing. All wireless medical devices involved in the procedure are sized such that they can be inserted and removed through an incision in the umbilicus.

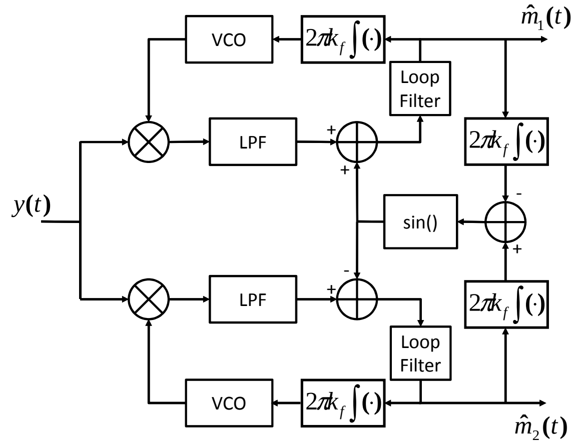


Fig. 2. A system block diagram of the MC-PLL to track all signal phases. Individual tracking PLL blocks are interconnected to remove interference caused by adjacent instantaneous frequencies.

We propose an alternative approach to HD wireless specifically for *in vivo* devices but practically applicable to other high data-rate links. For facility in explaining this concept, consider keeping the video signals in their analog formats prior to transmission. This allows significant savings in hardware by reducing the required analog-to-digital (ADC) conversions and latency caused by data compression and error correction. A multicarrier signaling, named instantaneous frequency-division multiplexing (IFDM), is proposed to transmit multiple analog signal carriers simultaneously in their "instantaneous frequency space" (Ford et al. 2013). This is achieved by using analog frequency modulation (FM) to transmit signals simultaneously and in the same frequency band. Instantaneous orthogonality of IFDM encoded signals is enforced by the intrinsic nature of how FM signals are generated. By exploiting unused portions of the spectrum in an instantaneous manner, multiplexing of analog signals is allowed in an otherwise occupied bandwidth. This overlapping of spectrum will potentially allow several analog signals representing the HD video to be transmitted in a bandwidth that is otherwise impossible and also in a small hardware footprint at the transmit sensor due to the minimalistic nature of analog FM radio circuits. Due to the smaller number of carriers, but increased processing gain of FM, this approach will also have improved PAPR relative to a digital multicarrier modulation and ideally achieve a similar throughput to traditional multicarrier modulations such as OFDM.

## 2. Instantaneous Frequency-division Multiplexing (IFDM)

One of the novel concepts behind IFDM is to analyze parallel data streams as analog signals rather than their digital counterparts in order to bypass hardware overhead and potential signal latency. Such an approach is especially well-suited for video links where image sensors can naturally output analog data. For example, imagine a wireless link where the luminance (Y) and chrominance (UV) signals, or other analog representations of HD video, are all compounded into a single bandwidth and transmitted simultaneously. For practical systems, multiple cameras could then be multiplexed at different carriers allowing for stereoscopic or panoramic surgical scenes. If possible, such an approach would go far in achieving the required metrics for small, high-rate devices since wireless analog systems are often smaller and simpler than their digital counterparts. Indeed, a wireless analog transmitter can be as simple/small as a few surface-mount passive and active components.

For wireless communications, all information bearing message signals must be upconverted to some frequency prior to transmission over the wireless medium. This upconversion is most often performed directly as in

$$x_i(t) = A_i m_i(t) \cos(2\pi f_c t) \tag{1}$$

where $A_i$ is the carrier amplitude, $f_c$ is the carrier frequency, and $m_i(t)$ is the analog message-bearing signal. Signals can then be multiplexed by choosing different carrier frequencies which forces orthogonality on transmitted signals. Though a somewhat archaic term, this type of modulation is referred to as amplitude modulation (AM) since information is contained in the envelope of the carrier. AM is not to be confused with traditional radio, though it shares similarities, as almost all modern communication physical layers use direct conversion as in (1).

For purposes of this work, IFDM signals are multiplexed and upconverted to the carrier frequency via FM

$$x_i(t) = A_i \cos\left(2\pi f_c t + 2\pi k_f \int_0^t m_i(\tau) d\tau\right) \tag{2}$$

where $k_f$ is the conversion "gain" from instantaneous voltage to instantaneous frequency. In order to separate each IFDM signal we first look at the composite signal arriving at the receiver

$$y(t) = \sum_{i=1}^{N} A_i \cos\left(2\pi f_c t + 2\pi k_f \int_0^t m_i(\tau) d\tau\right) + n(t) \tag{3}$$

where $n(t)$ is additive-white Gaussian noise (AWGN). To detect IFDM signals a receiver architecture is needed that can simultaneously track $N$ signals as different instantaneous frequencies (or phases) traverse the frequency band in the presence of noise. The key idea behind IFDM, that allows the multiple carriers to coexist in the same bandwidth, is to note that the instantaneous frequencies can be written as

$$\begin{aligned} f_i(t) &= \frac{d\Theta_i(t)}{dt} \\ &= 2\pi f_c + 2\pi k_f m_i(t) \end{aligned} \tag{4}$$

where $\Theta_i(t)$ is the instantaneous phase of the $i^{th}$ signal. In the time domain the message signals are linearly combined and not separable due to lack of orthogonality between messages. However, in the frequency domain, the signals are instantaneously orthogonal except when the frequencies are equal in which case no information is lost since the instantaneous frequency itself contains the message information. In other words, where two voltages on top of each other would add in the time domain, two frequencies on top of each other do not increase the frequency which is what contains the information. This concept of instantaneous orthogonality suggests the possibility of separating the overlapping signals and also the circuit to do so.

A new type of circuit is required to successfully demodulate the type of multicarrier signals proposed here - a multicarrier phase-locked loop (MC-PLL). Fig. 2 shows the proposed demodulating system block diagram for just two input signals; visually it is straightforward to extend to more signals though optimal filter coefficients become increasingly difficult to derive. As with any PLL-type system there are three types of states of interest at the output of the MC-PLL: lock, ambiguity, or catastrophic events. The locked state means the MC-PLL is successfully tracking the phase errors, and thereby the message signals, of all encoded

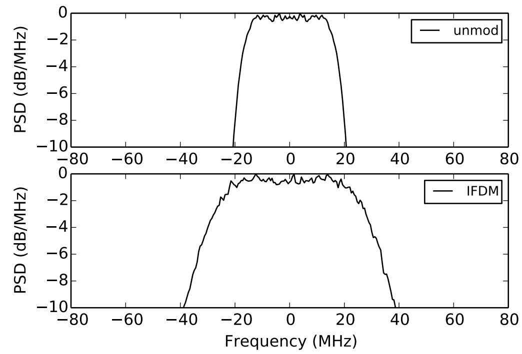


Fig. 3. Spectra of a single unmodulated baseband information signal (unmod) and the resulting IFDM signal with multiple signals in the same band and a $\beta = 2$ modulation index. The resulting bandwidth is slightly less than twice the unmodulated bandwidth.

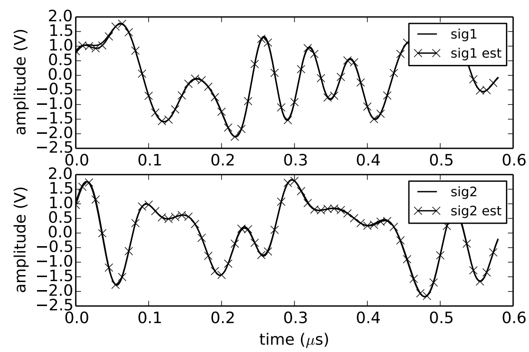


Fig. 4. Input (sig1 and sig2) and output (sig1 est and sig2 est) signals for IFDM. The signals were transmitted simultaneously in the same band but then separated with the MC-PLL.

signals. An ambiguity event occurs when the MC-PLL is in a locked state but the tracked signals may be ambiguous with each other; in other words, branch 1 of the MC-PLL may not be tracking signal 1. The final catastrophic event occurs when the IFDM signal falls out of lock and no tracking is possible of any of the signals. Such events can be mitigated by inserting training frames into the signals. For example, consider an HD video stream transmitting at 30 frames-per-second (30 fps). By allowing one (or more) frame(s) to be known at the receiver locked states can be more greatly increased by "training" the MC-PLL. In the following section, suboptimal loop filters and coefficients are used in the MC-PLL; however, simulation of the MC-PLL is shown to achieve lock on the multicarrier IFDM signals.

In addition to the detection system, the spectrum of any multicarrier or spreading system is important. If the bandwidth expansion of the signals is not effectively recovered through a higher data-rate then the spectral efficiency of the system is low and efficacy of the modulation is put in question. For example, a code-division multiple access (CDMA) system using direct-sequence spread spectrum (DSSS) that uses a spreading factor of 10 ideally can also achieve a multiplexing gain of 10 through orthogonality of the selected codes. Likewise, consider the spectrum of IFDM when two carriers are used. Power is equally divided between the two carriers and transmitted via FM with, in this example, a modulation index $\beta = 2$, yielding a bandwidth expansion of approximately two[1], as shown in Fig. 3. Though the bandwidth has been doubled the multiplexing has also, at least, been doubled securing a good spectral efficiency in the system with, hopefully, an increased output SNR common with FM systems. *This combination of multiple carriers in the same band and SNR gain of FM, along with the MC-PLL for demodulation, is the core idea of IFDM.*

## 3. Simulation Results

### 3.1. Analog Signal Tracking

To get an intuitive feel for IFDM consider two analog signals that are multiplexed using IFDM and then detected using the MC-PLL. For this simulation two randomly generated baseband signals with equal bandwidth of approximately 20 MHz are generated. These signals are IFDM modulated and corrupted with AWGN. The received signal is passed through the MC-PLL and each message estimate is then filtered with a spectrally-matched filter to improve the quality of the signal estimate. The bandwidth of these signals are

[1]This bandwidth is less than expected by Carson's rule for FM signals which is just an approximation.

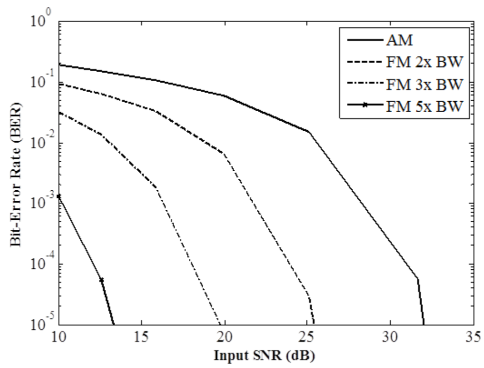


Fig. 5. Typical BER performance of digital communications in AWGN. Shown are performance curves when double sideband modulation (referred to as AM) is used or FM is used with various bandwidth expansions. Each modulation, regardless of type or bandwidth, has the same input power.

as that shown in Fig. 3. Noise is added to the received signal as described in (3). The received signal is input into the MC-PLL detector shown in Fig. 2 with the output of each branched matched filtered to the original signal. The filtered output of each branch of the MC-PLL is then compared to the filtered input signals as shown in Fig. 4. Though there is some transient behavior at early times, the MC-PLL is shown to successfully separate the message signals contained with the instantaneous frequency of the multicarrier waveform.

These simulation results are encouraging to pursue IFDM as a new modality of multicarrier modulation since multiple signals are mapped to different carriers and successfully recovered. It should be reiterated that the input IFDM signal occupies the same bandwidth as the largest bandwidth of all signals when frequency modulated; additionally, the latency of the MC-PLL output is negligible since, though there is some small transient behavior, the PLL operates on analog signals in real-time. Though, on average, the two frequency modulated signals are not orthogonal, the MC-PLL can still track each signal instantaneously thus effectively separating the signals as if they were transmitted orthogonally. Additionally, since the signals were frequency, rather than amplitude, modulated they will enjoy some immunity against amplitude variations caused by the AWGN channel.

### 3.2. Potential in Digital Systems

Though the focus of IFDM thus far has been demonstrating its application on analog signals in a low-power alternative for *in vivo* wireless video systems, IFDM also may have implications on digital systems. For example, any digital signal, regardless of the PHY layer used, is an analog signal as it propagates through the wireless medium; thus, digital waveforms can be analyzed using the proposed analog techniques as well. For example, consider randomly generated datastreams that are pulse shaped using a root-raised cosine filter. One such datastream can be upconverted and amplitude modulated which is typically done with wireless digital data. However, multiple of these datastreams, with smaller bandwidths, could be multiplexed using IFDM as described in this work. The modulation index of IFDM signals can be chosen such that the bandwidth of IFDM is equal to that of a single amplitude modulated stream. The advantage of this approach using IFDM is that analog signals, when frequency modulated, enjoy an SNR increase that has a quadratic relationship to the bandwidth expansion caused by FM.

Fig. 5 shows bit-error simulations for the AWGN channel when either FM or double sideband (DSB or AM with suppressed carrier) modulation is used. In both cases a single datastream, using the 64-PAM alphabet, is generated and modulated with either amplitude or frequency modulation. Noise is added to the modulated signal which is then demodulated with the appropriate optimal detection circuit. Bits are estimated at various signal and noise strengths. Fig. 5 shows BER performance for AM or FM at various bandwidth expansion factors. As expected, at sufficiently large SNR - to avoid the FM threshold effect - the FM system performs better due to a higher processing gain from bandwidth expansion of FM. In fact, the performance improvement is quite substantial for just a small bandwidth expansion. Future work will focus on combining this BER performance improvement when data is frequency modulated with the multiplexing afforded by IFDM to create a multicarrier system that exploits the analog SNR improvements of FM for high data-rate digital systems in future wireless communication links.

## 4. Conclusion

Next-generation wireless systems, including advanced biomedical devices and systems for advanced minimally invasive surgeries, will require wireless links to handle large data-rates such as from *in vivo* image sensors. This work has proposed a multicarrier transmission scheme that exploits traditional analog FM communication techniques, occupies a nominal bandwidth by a novel multiplexing approach, and also provides low-latency for delay-sensitive operations. This instantaneous frequency-division multiplexing (IFDM) benefits from SNR gains of analog signals that are frequency modulated and multiplexing streams on multiple carriers through IFDM. A new circuit architecture, the multicarrier phase-locked loop (MC-PLL) receiver, though derived heuristically, is shown to be able to track multiple signals though they occupy the same bandwidth and time. Future work on IFDM will focus on exploiting this analog effect on wireless digital signals.

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## References

Anderson, A., Lin, B. & Sun, Y. (2013), 'Virtually transparent epidermal imagery (VTEI): On new approaches to *in vivo* wireless high-definition video and image processing', *Biomedical Circuits and Systems, IEEE Transactions on* **7**(6), 851–860.

Artibani, W., Fracalanza, S., Cavalleri, S., Iafrate, M., Aragona, M., Novara, G., Gardiman, M. & Ficarra, V. (2008), 'Learning curve and preliminary experience with da Vinci-assisted laparoscopic radical prostatectomy', *Urol Int* .

Bashirullah, R. (2010), 'Wireless implants', *IEEE Microwave Magazine* **11**(7).

Castro, C., S., Smith, Alqassis, A., Ketterl, T., Sun, Y., Ross, S., Rosemurgy, A., Savage, P. & Gitlin, R. (2012), MARVEL: A wireless miniature anchored robotic videoscope for expedited laparoscopy, *in* 'Proc. IEEE Intl. Conference on Robotics and Automation'.

Chen, X., Zhang, X., Zhang, L., Li, X., Qi, N., Jiang, H. & Wang, Z. (2009), 'A wireless capsule endoscope system with low-power controlling and processing ASIC', *IEEE Trans. Biomedical Circuits and Systems* **3**(1), 11 –22.

Dung, L.-R. & Wu, Y.-Y. (2010), 'A wireless narrowband imaging chip for capsule endoscope', *IEEE Trans. Biomedical Circuits and Systems* **4**(6), 462–468.

Ford, S. et al. (2013), Instantaneous frequency division multiplexing (IFDM): An approach for wireless *in vivo* high definition video, *in* 'ASEE Southeastern Section 2013, Student Poster Session'.

Galluccio, L., Melodia, T., Palazzo, S. & Santagati, G. (2012), Challenges and implications of using ultrasonic communications in intra-body area networks, *in* 'Proc. 2012 9th Annual Conference Wireless On-demand Network Systems and Services (WONS)'.

Ghovanloo, M. & Najafi, K. (2004), 'A wideband frequency-shift keying wireless link for inductively powered biomedical implants', *IEEE Transactions on Circuits and Systems I* **51**(12).

Goldsmith, A. (2005), *Wireless Communications*, Cambridge University Press.

Han, S. H. & Lee, J. H. (2005), 'An overview of peak-to-average power ratio reduction techniques for multicarrier transmission', *Wireless Communications, IEEE* **12**(2), 56–65.

Hu, T., Allen, P., Hogle, N., & Fowler, D. (2008), Insertable surgical imaging device with pan, tilt, zoom, and lighting, *in* 'IEEE Int. Conf. on Robotics and Automation'.

Kai, S., Weiwei, Z. & Guangyu, W. (2013), Design and implementation of MDFT filter bank based multicarrier modulation systems, *in* 'Signal Processing, Communication and Computing (ICSPCC), 2013 IEEE International Conference on', pp. 1–6.

Kaul, S., Laungani, R., Sarle, R., Stricker, H., Peabody, J., Littleton, R. & Menon, M. (2007), 'Da Vinci-assisted robotic partial nephrectomy: Technique and results at a mean of 15 months of follow-up', *European Urology* pp. 186–192.

Mandal, S. & Sarpeshkar, R. (2008), 'Power-efficient impedance-modulation wireless data links for biomedical implants', *IEEE Trans. Biomedical Circuits and Systems* **2**(4), 301 –315.

Ohm, M., Schur, R. & Speidel, J. (2001), Extended lapped transforms for digital multicarrier modulation, *in* 'Global Telecommunications Conference, 2001. GLOBECOM '01. IEEE', Vol. 1, pp. 217–221 vol.1.

Proakis, J. G. & Salehi, M. (2008), *Digital Communications*, McGraw-Hill.

Rentschler, M., Dumpert, J., Platt, S., Farritor, S. & Oleynikov, D. (2007), 'Natural orifice surgery with an endoluminal mobile robot', *Journal of Surgical Endoscopy* pp. 1212–1215.

Shih, P.-J. & Shih, W.-P. (2010), 'Design, fabrication, and application of bio-implantable acoustic power transmission', *Journal of Microelectromechanical Systems* **19**(3).

Si, P., Hu, A., Malpas, S. & Budgett, D. (2008), 'A frequency control method for regulating wireless power to implantable devices', *IEEE Transactions on Biomedical Circuits and Systems* **2**(1).

Sun, Y., Anderson, A., Castro, C., Lin, B. & Gitlin, R. (2011), Virtually transparent epidermal imagery for laparo-endoscopic single-site surgery, *in* 'Proc. International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC'11)'.

Wu, C.-C., Li, C.-C. & Kao, F.-J. (2011), The high frequency magnetic induction driven miniature power module, *in* 'Proc. OptoeElectronics and Communications Conference (OECC)'.

Xingxin, G., Mingquan, L. & Zhenming, F. (2002), Optimal wavelet packet based multicarrier modulation over multipath wireless channels, *in* 'Communications, Circuits and Systems and West Sino Expositions, IEEE 2002 International Conference on', Vol. 1, pp. 313–317 vol.1.

Zhang, Q., Feng, P., Geng, Z., Yan, X. & Wu, N. (2011), 'A 2.4-GHz energy-efficient transmitter for wireless medical applications', *IEEE Trans. Biomedical Circuits and Systems* **5**(1), 39 –47.