Frequency Band Selection and Channel Modeling for WNSN Applications using SimpleNano

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***Abstract*—With the discovery of Graphene, different nano-scale components can be integrated to form a nano-sensor capable of transmitting in the tera-hertz range (0.1-10 THz). The transmitted signal gets attenuated when it passes through different types of molecules. Thus, channel models for wireless nano sensor networks (WNSN) are environment specific. For most of the applications, the nano-sensors are placed inside the human body, which may interact with other nano-sensors (inside the body) and other non nano-scale devices (outside the body). We present SimpleNano, a simple and novel channel model for WNSN applications in the tera-hertz range. SimpleNano is an approximation to log-distance path loss model along with the random (log-normally distributed) attenuation caused by the molecular absorption. For certain band windows within tera-hertz range SimpleNano experiences low molecular noise. These different band windows have been compared for a novel capacity performance metric i.e. spatial capacity per Hertz and the results prove that the proposed band windows achieve better throughput than the ones with larger molecular noise.**

***Index Terms*—Wireless nano sensor networks, Graphene, Channel modeling, channel capacity.**

I. INTRODUCTION

Wireless nano sensor network (WNSN) is an interconnection of very small nano-scale devices exchanging information among themselves as well as with other non nano-scale devices. Graphene and it's derivatives, due to their incredible electrical and electromagnetic properties, have enabled the production of different nano scale components, that can be integrated to form a nano-sensor [1], [2]. Graphene based nano-sensors may sense and store information, actuate different processes, and transmit information by emitting EM waves [3]. A bottom up approach for a complete wireless nano scale communication model has been proposed in [4]. The road map includes nano-antenna theory, frequency band selection, channel modeling, information encoding and modulation techniques to form a protocol for specific WNSN applications.

Most of the new promising WNSN applications are in biomedical field [3]. WNSNs could be used to report the measurements for drug delivery and is thought to be the future technology for the treatment of dangerous diseases such as cancer. Different types of nano sensors are recently being built that can detect sodium, glucose, cholesterol and cancer bio-marks in the blood while different infectious agents such as lung cancer cells, asthma attacks, influenza, malaria viruses and parasites can also be detected [1]. All these application require complex processing and cover a very large area when considered on a nano scale. Naturally, a network of nano sensors is required in which nano sensors efficiently communicate with other nano-sensors as well as with other non nano-scale devices for measurement reporting and control.

Recently proposed Graphene based nano antennas can efficiently radiate in 0.1-10 THz range [5]. In this frequency range, the signal can penetrate into a wide variety of non-conducting materials, therefore this unlicensed spectrum has recently been used in medical imaging and high bandwidth wireless networking applications [6] [7]. A propagation model has been developed for WNSN in [8] which gives the path loss as a function of frequency and distance. However, this path loss model becomes increasingly complex for mediums such as human body and air because of the presence of molecules of multiple types. Furthermore, it is highly frequency dependent which also is not a very desirable feature for channel models.

We present SimpleNano, a simple and novel channel model for WNSN applications in the tera-hertz range. SimpleNano is a channel model build for complex mediums such as human body and air and can easily be extended to other mediums if the concentration and type of molecules are known. SimpleNano is an approximation to log-distance path loss model along with the random (log-normally distributed) attenuation caused by the molecular absorption (typically water molecules). The results show that for certain band-windows SimpleNano experiences low molecular attenuation and molecular noise. Finally, different band windows have been compared for a novel capacity performance metric i.e. spatial capacity per Hertz.

The rest of the paper has been organized as follows. In Section II, analysis of molecular attenuation for mediums air and human body has been presented. The frequency band selection in THz band has been discussed in Section III. Thereafter, SimpleNano has been described and analyzed in Section IV followed by the spatial capacity analysis in Section V. Finally, Section VI concludes this paper.

II. MOLECULAR ATTENUATION

Molecular attenuation can be defined as the loss of energy due to the vibration of molecules at different set of frequencies for different molecules. The parameter absorption coefficient or attenuation coefficient is a quantity that describes how easily an EM wave can propagate through a medium. Larger the absorption coefficient, larger is the attenuation provided by the medium. The ratio of received power to the transmitted power when passed through a certain medium depends on the

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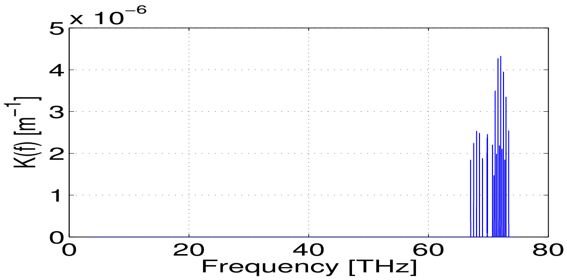


Fig. 1. Absorption Coefficient of 78% Nitrogen

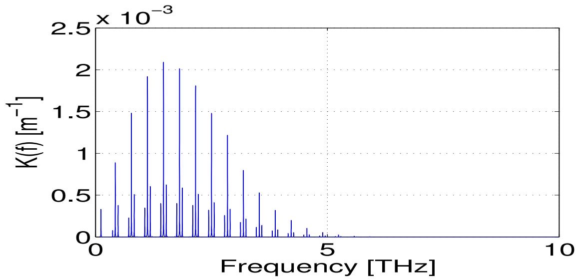


Fig. 2. Absorption Coefficient of 21% Oxygen

concentration and type of the molecules present in the medium [8] [9] which is given as:

$$\left(\frac{P_r}{P_t}\right)_{abs}(f,d) = e^{-K(f)d} \tag{1}$$

where P_t and P_r are the transmitted and the received power respectively, f stands for frequency, d is the distance covered by transmitted signal and $K(f)$ is the medium absorption coefficient (MAC). The MAC varies when the molecules vibrate with different frequencies. The MAC also depends on the concentration of a particular molecule in the propagation medium. It is the sum of individual absorption coefficients of all types of molecules present in medium. All the individual MACs can be found on HITRAN database [10] for known concentrations and types of molecules forming a medium.

A. Molecular Attenuation for Air

Air is composed of approximately 78% Nitrogen, 21% oxygen and 1% of other gases. The MAC $K(f)$ for air can be written as:

$$\begin{aligned} K(f)_{air} &= K(f)_{1-5\%H_2O} + K(f)_{78\%N_2} + \\ &+ K(f)_{21\%O_2} + K(f)_{1\%\text{Other gases}} \end{aligned} \tag{2}$$

Fig 1 shows the MAC for a medium having 78% Nitrogen and it can be observed that Nitrogen molecules provide absorption in frequencies much higher than the frequency of operation of nano sensors (100GHz-10 THz). Fig 2 shows the MAC for a medium having 21% oxygen which provides very low absorption at frequencies in THz range particularly for $f > 5$ GHz. For very large distances, these absorptions may cause significant attenuation to the propagating wave, however due to limitted transmitted energy, WNSN applications are only limited to small or medium range distances. The 1% of other gases present in the air either do not cause absorption in the band of interest or have very low absorptions similar to oxygen. The most significant absorption in the band of interest has been found for water vapors whose concentration varies from 1 to 5 % in the air depending upon the area and the weather conditions. The attenuaton caused by water vapors to propagating wave is far more significant than the attenuation caused by all the other molecules (nitrogen, oxygen and other gases). Therefore, MAC of air (eq. 2) reduces to:

$$K(f)_{air} = K(f)_{1-5\%H_2O} \tag{3}$$

Human Body parts	% in Human body	% water molecules
Bones	15	22
Muscles	38	75
Blood	8	83
Skin	16	72
Fat	20	12
Others	3	-

TABLE I
AVERAGE CONCENTRATION OF WATER MOLECULES IN DIFFERENT PARTS OF HUMAN BODY

B. Molecular Attenuation in Human Body

Human body is composed of approximately 15% of bones, 38% of muscles, 8% of blood, 20% of fat, 16% of skin and 3% of other body parts. Water molecules are the largest amount of molecules present in human body. Table I compares average concentration of water molecules in different parts of human body. Again, the attenuation caused by the water molecules is far more significant as compared to the other molecules in human body, therefore, the MAC for human body has been taken as weighted average of the absorption coefficients of water molecules present in different body parts as described in the eq. 4.

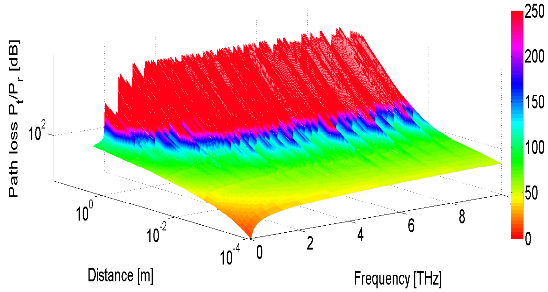
$$\begin{aligned} K(f)_{\text{HB}} &= 0.15 \times K(f)_{22\%H_2O} + 0.38 \times K(f)_{75\%H_2O} + \\ &+ 0.08 \times K(f)_{83\%H_2O} + 0.16 \times K(f)_{72\%H_2O} + \\ &+ 0.2 \times K(f)_{20\%H_2O} + 0.03 \times K(f)_{\text{Others}} \end{aligned} \tag{4}$$

III. FREQUENCY BAND SELECTION IN TERA-HERTZ BAND

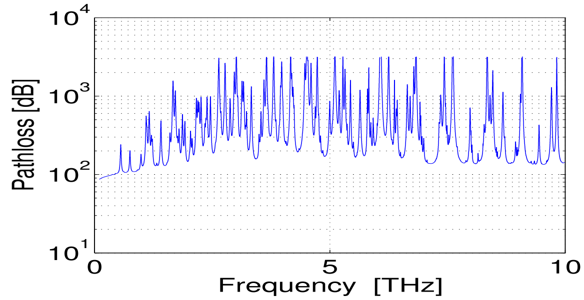
In [8], a new THz path loss model has been introduced for WNSNs given as:

$$P_L(f,d) = \frac{P_t}{P_r}(f,d) = \left(\frac{4\pi f d}{c}\right)^2 \times e^{K(f)d} \tag{5}$$

where $K(f)$ is the MAC which depends upon the medium composition. The above model becomes increasingly complex for complex mediums like air and human body so instead of suming all individual MACs of all molecules present in the medium we propose to compute the resultant MACs from eq. 3 and eq. 4 respectively. We can observe that path loss is very frequency selective and increases with the distance from the 3-D path loss plotted in Fig 3(a) as a function of frequency and distance for human body. The frequency selectivity of the path loss is more evident from Fig. 3(b) where the path loss experienced has been plotted over the entire frequency range for a fixed distance ($d = 0.5m$).



(a) 3-D Path loss in Human Body as a function of frequency and distance



(b) 2-D Path loss in Human body at $d = 0.5m$

Fig. 3. 3-D and 2-D Path loss in Human Body

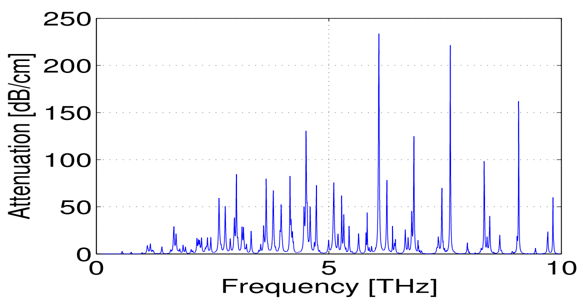


Fig. 4. Attenuation caused by water molecules in human body

Windows	Range $[THz]$	Band-width	Mean Attenuation HB$[dB/cm]$	Mean Attenuation Air$[dB/cm]$
W_0	0.1-10	9.9	8.46	0.4853
W_1	0.1-0.5	0.4	0.021	0.000682
W_2	0.8-0.9	0.1	0.087	0.000821
W_3	7.1-7.2	0.1	0.298	0.000279
W_4	7.8-7.9	0.1	0.3665	0.0037

TABLE II
MEAN ATTENUATION OF DIFFERENT FREQUENCY WINDOWS IN AIR AND HUMAN BODY

A. *Choice of frequency windows*

At very low distances (much lower than 1m), the effect of molecular absorption is very low and thus the entire band (100 GHz to 10 THz) can be used for communication between nano sensors (see Fig. 3(a)). But for larger distances, a careful choice for the band of operation must be made in order to experience minimized molecular attenuation. Fig. 4 shows the attenuation in dB/cm, caused by the water molecules, for medium human body. A similar pattern has been observed for attenuation in medium air. Five Frequency windows have been determined in which attenuation is very low having mean attenuation below 0.5 dB/cm. Table II gives the mean attenuation for different frequency windows in dB/cm for the two mediums. It can be seen that a 400 GHz wide band from 100-500 GHz has a mean attenuation of 0.021 dB/cm in human body. Thus, the choice for the transmission band should be made on the link distance and the mean attenuation experienced in the medium for that window.

IV. SimpleNano

Most of the analytical or empirical path loss models can be approximated to log distance path loss with random attenuation due to the objects (shadowing) [11], [12] written as:

$$\frac{P_t}{P_r}[dB] = 10\log_{10} K_0 + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \qquad (6)$$

where K_0 is the path-loss at a reference distance d_0, n is the path loss exponent and X_σ is a log-Normal random variable that takes into account the attenuation caused by the objects in the path (shadowing) [11]. The path loss for WNSNs, described in Section III, can also be approximated to simplified path loss and shadowing model named as SimpleNano.

In SimpleNano, the reference distance, d_0, has been chosen to be be $0.01m$. This distance must lie in the far field region ($d_0 > d_f$) [12] such that

$$d_f = \frac{2D^2}{\lambda} \qquad d_f >> D \qquad d_f >> \lambda \qquad (7)$$

where D is the largest dimensions of the antenna and has been taken to be $1\mu m$ as per [5] and λ corresponds to the wave length for the THz frequency range (0.1-10 THz).

In typical path-loss models, the path loss is not a function of frequency. For ultra wide-band communications, the path loss is usually represented as an average over all frequencies [13],[14].

$$P_L(d) = \frac{1}{N}\sum_{i=1}^{N} |H(f_i, d)|^2 \qquad (8)$$

where $H(f_i, d)$ is the frequency response at a distance d and frequency f_i. The path loss for WNSN applications can also been calculated in a similar way where $H(f_i, d)$ is the simulated frequency response and N is number of observed frequencies in the THz range. The simulated path loss has been used to calculate path loss exponent n.

A. *Log Normal Molecular Shadowing*

The random molecular attenuation in SimpleNano has been validated by law of large numbers since there are large number of attenuating molecules present between the transmitter and the receiver. Specifically, the power loss due to molecular absorption is defined as:

$$\frac{P_t}{P_r} = e^{K \sum_i^m d_i} \tag{9}$$

where K is mean of the individual MACs, d_i is diameter of i^{th} molecule and m is the number of attenuating molecules present in the path. For mediums such as human body or air, there would be random number of water molecules present in a path for a given distance because of the varying location of nano sensors. For instance, the MAC for a nano sensor present in the muscles communicating with another sensor in the skin will be different from the MAC for a nano-sensor present in the blood communicating with the same sensor separated by an identical distance.As large number of attenuating molecules are present between transmitter and receiver, therefore, by central limit theorem, we can approximate K to be a Gaussian random variable and therefore, by eq. 9, the power loss due to molecular absorption has a log-Normal distribution with mean μ_{dB} standard deviation $\sigma_{X_{dB}}$:

$$P(X_{dB}) = \frac{1}{\sqrt{2\pi}\sigma_{X_{dB}}} exp\left[\frac{-(X_{dB} - \mu_{dB})^2}{2\sigma^2_{X_{dB}}}\right] \tag{10}$$

Therefore, the net path loss for a THz waves propagating in human body or air can be modeled by eq. 6. In order to validate the proposed model, simulations have been conducted for three different distance ranges to determine the path loss exponent n and standard deviation $\sigma_{X_{dB}}$. Instead of taking the minimum mean-square error (MMSE) fit to empirical measurements, simulated results have been used for the computation of n and $\sigma_{X_{dB}}$ for mediums such as human body and air. The variations in the simulated path loss (8) are due to the varying number of water molecules in different parts of human body parts and air. Although the results can not be generalized as they are not based on empirical measurements, still these results can be used to compare n and $\sigma_{X_{dB}}$ for different band windows. The three distance ranges i.e. very short (0.00001-0.01 meters), short (0.01-2m) and medium (1-20m) have been considered.

It can be observed from Fig. 3 that for very short distances, the molecular absorption is negligible. Attenuating peaks due to molecular absorption are seen far above $0.01m$ in air and human body. It can be concluded that for very short distances, the molecular absorption is deterministic irrespective of medium. Therefore, for such small distances, the free space path loss model can be used directly to compute the path loss. The proposed model has been used to model the path loss for short and medium range distances. In the following, the details for the computation of the path loss exponent n and the standard deviation $\sigma_{X_{dB}}$ are presented for short and medium range distances.

1) Short Range Model in Medium Air: Following, a minimum mean-square error (MMSE) fit to the simulated results, the path loss exponent n_0 and the standard deviation σ_0 for short range distances have been tabulated in Table III for all the windows described in Section III. It can be observed that σ_0 is quite low for all the windows. Hence, for short distances in air, all the band windows can be used for communication as the attenuation caused by the molecular absorption (controlled by σ_0) is very low in all the windows.

Windows	Range	Bandwidth	n_0	σ_0
W_0	0.1-10	9.9	4	0.231
W_1	0.1-0.5	0.4	4.0	0.025
W_2	0.8-0.9	0.1	4.0	0.028
W_3	7.1-7.2	0.1	4.0	0.0065
W_4	7.8-7.9	0.1	4.0	0.124

TABLE III
PATH LOSS EXPONENT, n_0, AND STANDARD DEVIATION, σ_0, FOR SHORT RANGE DISTANCES IN AIR

Windows	Range	Bandwidth	n_1	σ_1
W_0	0.1-10	9.9	4.4	5.49
W_1	0.1-0.5	0.4	4.0	0.21
W_2	0.8-0.9	0.1	4.0	0.277
W_3	7.1-7.2	0.1	4.0	0.06
W_4	7.8-7.9	0.1	4.0	0.832

TABLE IV
PATH LOSS EXPONENT, n_1, AND THE STANDARD DEVIATION, σ_1, FOR MEDIUM RANGE DISTANCES IN AIR

2) Medium Range Model in Medium Air: The results for the computation for the path loss exponent n_1 and standard deviation σ_1 for medium range distances in air have been compared in Table IV. It can be observed from table IV that instead of the entire THz band, W_0, different windows such as W_1, W_2, W_3 and W_4 can be used owning to a low σ_1 and hence lower molecular attenuation. For instance, W_1 having a bandwidth of 0.4 THz has $\sigma_1 = 0.21$ and since the bandwidth is larger than W_2, W_3 and W_4, this band window can support larger capacity as compared to other windows.

3) Short Range Model in Human Body: The concentration of water molecules is much larger in human body as compared to air, therefore a larger standard deviation or σ_2 is expected. The results in Table V shows that all windows except for W_1 have very large standard deviation and thus can not be used for human body. The band window W_1 has comparatively lower standard deviation ($\sigma_2 = 1.5$) than other windows and thus it's the only window that can be used in human body.

4) Hybrid Medium Range Model in Human Body and Air: A nano sensor present in the human body must communicate with an external non nano-scale device, and in this case, the EM wave will pass through two different mediums i.e. air and human body. A dual slope path loss model is proposed with a path loss exponent n_2 and σ_2 (in human body $d \leq 1.7m$) and thereafter the power falls of with a path loss exponent n_1 and σ_1 (in air) mathematically written as:

$$\frac{P_t}{P_r}[dB] = \begin{cases} 10\log_{10} K + 10n_2 \log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma_2} \\ \text{if} \quad d_0 \leq d \leq 1.7 \\ 10\log_{10} K + 10n_2 \log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma_2} + \\ 10n_1 \log_{10}\left(\frac{d}{d_c}\right) + X_{\sigma_1} \text{if } d_c \leq d \leq 20 \end{cases} \tag{11}$$

V. SPATIAL CAPACITY FOR DIFFERENT BAND-WINDOWS

Typical narrow band communication systems aim to improve the spectral efficiency of the system, measured in bps/Hz as bandwidth is one of the most valuable resource for

Windows	Range	Bandwidth	n_2	σ_2
W_0	0.1-10	9.9	5.5	14.0
W_1	0.1-0.5	0.4	4.15	1.5
W_2	0.8-0.9	0.1	4.8	8.5
W_3	7.1-7.2	0.1	6.9	29
W_4	7.8-7.9	0.1	7.4	33.9

TABLE V
PATH-LOSS EXPONENT AND VARIANCE FOR SHORT RANGE DISTANCES IN HUMAN BODY

Channel	Window	Distance $[m]$	Spatial capacity $[Tbits/m^2]$	Spatial Capacity/Hz $[Tbits/m^2/Hz]$
Air	W_0	2	4.0882	0.4129
Air	W_1	2	1.0604	2.6510
Air	W_2	2	0.21213	2.1213
Air	W_3	2	0.0011	0.0112
Air	W_4	2	1.566810^{-6}	1.566810^{-5}
HB	W_0	1.7	1.7672	0.1785
HB	W_1	1.7	1.1679	2.9198
HB	W_2	1.7	0.19221	1.9221
HB	W_3	1.7	26.705810^{-12}	2.670610^{-10}
HB	W_4	1.7	0.064010^{-12}	6.400010^{-13}
Air	W_0	20	0.0013957	0.0014
Air	W_1	20	0.0074	0.0184
Air	W_2	20	0.0013	0.0131
Air	W_3	20	1.218710^{-8}	1.218710^{-7}
Air	W_4	20	14.969410^{-12}	1.496910^{-10}

TABLE VI
SPATIAL CAPACITY COMPARISON FOR DIFFERNENT WINDOWS IN HUMAN BODY AND AIR

such systems. Nano communication systems strive to improve the power efficiency as power or energy is the most critical resource for such systems. The use of sub pico-second long base band modulated pulses has been proposed in [15]. Limited transmitted power for WNSNs can be compensated by the use of extremely large bandwidth, so instead of spectral capacity Tbps/Hz spatial capacity Tbps/m^2 and spatial capacity per Hertz have been used as the performance metrics for WNSN.

For the computation of capacity, we have only used the molecular noise caused by the water molecules. Using MAC's introduced in section II, noise power spectral densities for air and human body have been evaluated by following an approach presented in [9]. Unlike AWGN, the molecular noise is colored. Channel capacity has been evaluated using Capacity formula of a time invariant frequency selective fading channels [11] as follows:

$$C = \sum_i B_i log_2(1 + \frac{|H(f_i)|^2 P_i}{N_i}) \tag{12}$$

where B_i is the bandwidth of the i^{th} sub-band and N_i is the noise power spectral density of the i^{th} band introduced in [9]. Results show that WNSN can achieve extremely high data rates by carefully selecting the frequency bands within THz region. Results also prove that windows having low molecular attenuation also have lower molecular noise.

Table VI shows the comparison of capacity for short and medium range nano applications. As the capacity is directly proportional to the bandwidth, therefore we introduce a new performance metric which is spatial capacity per Hertz in order to do a fair comparison. It can be observed that W_1 gives the highest spatial capacity per Hertz for all the scenarios. Windows W_3 and W_4 result in a poor performance because of the high molecular attenuation (see Table II). All these results are in total agreement with the results of frequency band selection with SimpleNano presented in Section IV where it has been argued that in human body, frequency bands other than W_1 can not be used while for short range in air almost all the bands can be used.

VI. CONCLUSION

In this paper, a new and simple propagation model in THz range, namely SimpleNano, has been presented for complex mediums such as air and human body. SimpleNano models the path loss as the sum of the free space path loss and random attenuation caused by the absorption of the wave by the the molecules. The research showed that only the water molecules contribute significantly to the attenuation of the waves in both these mediums. Certain frequency bands have been identified where molecular noise and molecular attenuation is relatively low, having very high bit rates and therefore can be used for communication in WNSN applications.

REFERENCES

[1] I. Akyildiz, F. Brunetti, and C. Blazquez, "Nanonetworks: A new communication paradigm," *Computer Networks (Elsevier) Journal*, vol. 52, pp. 2260–2279, Aug 2008.
[2] J. She and J. Yeow, "Nanotechnology-enabled wireless sensor networks: From a device perspective," *Sensors Journal, IEEE*, vol. 6, pp. 1331 – 1339, oct. 2006.
[3] I. F. Akyildiz and J. M. Jornet, "Electromagnetic wireless nanosensor networks," *Nano Communication Networks (Elsevier) Journal*, vol. 1, no. 1, pp. 3–19, March 2010.
[4] I. F. Akyildiz and J. M. Jornet, "The internet of nano-things," *IEEE Wireless Communication Magazine*, vol. 17, no. 6, pp. 58–63, December 2010.
[5] J. M. Jornet and I. F. Akyildiz, "Graphene-based nano-antennas for electromagnetic nanocommunications in the terahertz band," in *Fourth European Conference on Antennas and Propagation, EUCAP*, April 2010.
[6] B. Zhu, Y. Chen, K. Deng, K. Hu, and Z. Yao, "Terahertz science and technology and applications," in *PIERS Proceedings*, 2009.
[7] H. Kitahara, M. Tani, M. Hangyo, Y. Miura, T. Sawai, and J. Nishizawa, "Application of thz imaging for medical diagnostics," in *Quantum Electronics Conference, 2005. International*, pp. 1238 – 1239, 11, 2005.
[8] J. M. Jornet and I. F. Akyildiz, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band," *IEEE Transactions on Wireless Communications*, vol. 10, pp. 3211–3221, October 2011.
[9] J. M. Jornet and I. F. Akyildiz, "Channel capacity of electromagnetic nanonetworks in the terahertz band," in *IEEE International Conference on Communications, ICC, Cape Town, South Africa*, May 2010.
[10] L. Rothman, I. Gordon, A. Barbe, D. C. Benner, P. Bernath, D. C. M.Birk, V. Boudon, L. Brown, and A. Campargue, "The hitran 2008 molecular spectroscopic database," *Journal of Quantitative Spectroscopy and Radiative Transfer*, vol. 110, pp. 553–572, Jun 2009.
[11] A. Goldsmith, *Wireless Communications*. Cambridge University Press, September 2005.
[12] T. S.Rappaport, *Wirless Communication Principles and Practice,2nd Edition*. Prentice Hall; 2 edition, Jan 2002.
[13] S. S.Ghassemzadeh, "An empirical indoor path loss model for ultra-wideband channels," *Journal of Communications and Networks*, December 2003.
[14] S. S. Ghassemzadeh and V. Tarokh, "The ultra-wideband indoor path loss model," tech. rep., IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs), June 24, 2002.
[15] J. M. Jornet and I. F. Akyildiz, "Information capacity of pulse-based wireless nanosensor networks.," in *SECON*, pp. 80–88, IEEE, 2011.