Chude-Okonkwo et al. EURASIP Journal on Advances in Signal Processing 2011, 2011:123
http://asp.eurasipjournals.com/content/2011/1/123

EURASIP Journal on Advances in Signal Processing
a SpringerOpen Journal

RESEARCH Open Access

# Time-scale domain characterization of non-WSSUS wideband channels

Uche AK Chude-Okonkwo*, Razali Ngah and Tharek Abd Rahman

## Abstract

To account for nonstationarity, channel characterization and system design methods that employ the non-wide-sense stationary uncorrelated scattering (non-WSSUS) assumption are desirable. Furthermore, the inadequacy of the Doppler shift operator to properly account for the frequency shift in wideband channel implies that the time-frequency characterization methods that employ the Doppler shift operator are not appropriate for most wideband channels. In this article, the statistical time-scale domain characterization of the non-WSSUS wideband channel is presented. This approach employs the time scaling operator in order to account for frequency spreading, and also emphasizes on the nonstationarity of the wideband channel. The non-WSSUS statistical assumption termed local-sense stationary uncorrelated scattering (LSSUS) is presented and employed in characterizing the nonstationary property of the time-varying wideband channel. The LSSUS channel model is then parameterized to provide useful coherence and stationarity/nonstationarity parameters for optimal system design. Some application relevance of the developed model in terms of channel capacity and diversity techniques are discussed. Measurement and simulation results show that the assumption of ergodic capacity and the performance of various diversity techniques depend on the degree of channel stationarity/nonstationarity. It is shown that the quantification of this degree of stationarity through the channel parameters can provide a way of tracking channel variation and allowing for adaptive application of diversity techniques and the channel capacity.

**Keywords:** time-scale domain, non-WSSUS, wideband, diversity techniques, ergodic capacity

## 1 Introduction

Time-varying channels are often modeled as stationary random processes using the concept of the wide-sense stationary uncorrelated scattering (WSSUS) assumption [1]. This stationarity assumption leads to simplification of transceiver design and may in some circumstances be reasonable on physical grounds. In this case, the multiple channel states presented by the mobility of the communication terminal(s)/scatterer(s) have varying channel statistics over the transmission duration, and it is assumed that the variances among the statistics of the multiple channels are insignificant, so they can be averaged out over a wide range of interval. The assumption of the statistical stationarity of the time-varying channel allows for the definition of some channel parameters that are employed in system designs.

Unfortunately, in practice the WSSUS assumption is not often met. The nature of the time-varying channel is such that the spatial structures of the multipath components, i.e., their number, time-of-arrivals, angle-of-arrivals (AOA), and magnitudes, change with time and location, leading to nonstationary statistics [2,3]. More also scattering by the same object as well as variation in the AOA caused by mobility with respect to a statistical stationary duration of reference may result in correlation among scatterers. This condition violates the uncorrelated scattering assumption. And like stationarity, nonstationarity also carries informative features of the channel. Hence, developing approaches that would tap into the information that can be obtained from nonstationary analysis of the channel will be of great merit to optimal system design.

Typically, time-varying channels are characterized by time and frequency dispersions. When using Doppler shift as a measure of the channel's frequency dispersion, it is presumed that composite (multi-tone) signals or

* Correspondence: uche@utm.my
Wireless Communication Centre, Universiti Teknologi Malaysia, 81310 UTM, Skudai, Johor, Malaysia

subcarriers (in the case of multicarrier systems) passing through the channel, experience the same amount of frequency shift obtained with respect to the carrier frequency $f_c$. For narrow bandwidth composite signals, this approximation may be practically true and the presentations in [2], sufficient. However, for wide-bandwidth signals, the Doppler approximation wholly fails since the composite signals experience different Doppler shifts. This is the case of ultrawideband (UWB) and underwater acoustic (UWA) channels. Therefore, channel characterization methods that do not depend on the carrier frequency to obtain the measure of frequency dispersion in wideband channels are much desired. One of such method is the time-scale domain channel characterization [4-10].

The delay-Doppler effects of time-varying channel are often modeled as taps of a time-varying filter [11,12]. In the case of the narrowband channel, one tap is the sum of many paths. Hence, it is acceptable to characterize the time evolution of the individual taps using an autocorrelation function (ACF) model which is assumed to be independent across delay. Therefore, in non-WSSUS characterization, the time evolution model of the narrowband channel can be decomposed into the time evolution of individual taps. This is not the case for the UWB channel where taps are often composed of few or no paths due to the fine time resolution. The fine time resolution implies narrow delay bins which enable paths to move fast from one tap to another [13]. Hence, the time evolution of taps becomes correlated across delays. In this case, the narrowband assumption of modeling the stochastic process of taps independent across delay no longer holds. So, the time evolution of the UWB channel cannot be decomposed into the time evolution of the individual taps, but of the individual paths. Therefore, the non-WSSUS characterization of the narrowband channel will differ significantly from that of the wideband channel.

In this article, we attempt to answer the following questions. (1) How can the time-varying non-WSSUS wideband channel be characterized in the time-scale domain? (2) What are the necessary parameters and information that can be obtained from the non-WSSUS model? (3) How can such information be used in system design in order to optimize performance? To address these questions, we present the non-WSSUS time-scale domain characterization method for time-varying wideband channel which employs the assumption that the channel statistics are locally stationary. This method is considered appropriate for wideband nonstationary channels. The main contributions of this article which sort to answer the three questions posed above are outlined as follows.

- A method of characterizing the non-WSSUS wideband channels using a statistical concept termed LSSUS assumption is presented in the time-scale domain. The LSSUS concept results primarily from the designation of statistical intervals of quasi-stationarity and quasi-nonstationarity over which the WSSUS and LSSUS assumptions can be jointly defined. The closed-form expression for the LSSUS channel is derived bearing in mind that the stationarity/nonstationarity interval is dependent on the properties of the transmit signal and the wireless channel. We note that this LSSUS closed-form expression can be applied to most channels, but in terms of merit, it is more appropriate for the characterization of the wideband channels like acoustic, sonic, UWB channels, and other emerging systems operating at high fractional bandwidths; in which case the concept of time scaling is more suitable than Doppler shift. In the narrowband channel, the LSSUS expression when presented in the time-frequency domain can be deem to be equivalent to the channel correlation function (CCF) in [2] as will be explained in Section 4.
- To parameterize the non-WSSUS channel in time-scale domain using the LSSUS assumption, a stationarity degree estimation method is presented. This estimator uses the concept in [14] to quantify the extent to which an 'instantaneous' scattering functions deviates from a given one assumed to be statistically stationary (WSSUS). The stationarity degree is used to obtain condensed coherence and stationarity parameters that are equivalent to those presented in [2]. However, unlike in [2] the approach here emphasizes on the frequency dependence of these parameters, particularly, the coherence/stationarity time.
- The illustration and application relevance of the LSSUS concept to the time-varying wideband communication systems is presented. Illustrative measurement and simulation examples for the time-varying UWB channel typical of the infostation [15-17] environment are provided. And simulation with numerical results in the case of a simplified underwater communication scenario is also presented. These simulations and measurements are used to show the merit and application of the LSSUS concept to improving system performance by the optimal application of ergodic capacity assumption and diversity techniques.

The rest of this article is organized as follows. In Section 2, the relevant studies that are related to the idea developed in the article are presented. The basic time-scale channel model is specified in Section 3. In Section 4, the WSSUS characterization of the wideband channel in the time-scale domain is presented. Section 5 is devoted to the non-WSSUS characterization of the time-varying wideband channel using the LSSUS assumption. The estimation of the non-WSSUS channel stationarity degree and the derivation of LSSUS channels parameters are presented in Section 6. In Section 7, the application relevance of the LSSUS model in relation to channel ergodic capacity assumption and diversity techniques is presented. In Section 8, measurement and simulation examples are used to illustrate the concept and application of the LSSUS model. Conclusions are given in Section 9.

## 2. Related studies

Some of the existing studies related to the ideas presented in this article are as follows. In his seminal paper [1], Bello highlighted on the discrepancy between the WSSUS and non-WSSUS channels using the term Quasi-WSSUS (QWSSUS). The QWSSUS assumption implies that the channels statistics do not change within a specific time and frequency interval. A more rigorous and classical theoretical framework for the description of the non-WSSUS channels was introduced by Matz [2], where instead of the WSSUS scattering function, the local scattering function (LSF), in consonance with the concept of time-dependent spectrum for nonstationary analysis, was defined. And the time-frequency CCF appropriate for the non-WSSUS case was also delineated. The LSF and CCF are given respectively as [2]

$$C_{\mathbf{H}}(t,f;\tau,\upsilon) = \int\int R_{\mathbf{L}}(t,f;\Delta t,\Delta f)e^{-j2\pi(\upsilon\Delta t-\tau\Delta f)}d\Delta t d\Delta f \quad (1)$$

and

$$A_{\mathbf{H}}(\Delta t,\Delta f;\Delta\tau,\Delta\upsilon) = \iint\iint C_{\mathbf{H}}(t,f;\tau,\upsilon)e^{-j2\pi(\Delta\upsilon t-\Delta\tau f)} .\times\ e^{-j2\pi(\upsilon\Delta t-\tau\Delta f)} \quad (2)$$

where $R_{\mathbf{L}}(t, f; \Delta t, \Delta f)$ is the autocorrelation of the time-varying transfer function which in this case is viewed as a nonstationary random process.

Equation 2 implies that $A_{\mathbf{H}}(\cdot)$ is the 4-D Fourier transform of (1). Hence, the function $A_{\mathbf{H}}(\cdot)$ is a complete characterization of the narrowband non-WSSUS channel. While the coherence parameters were defined using the conventional approach in [11,12], the stationarity parameters in time and frequency were defined as the inverse of some normalized maximum delay and Doppler spread weighted integrals, respectively. The direct computation and measurement of $A_{\mathbf{H}}(\cdot)$ and subsequently, the stationarity parameters, are somewhat obdurate. Therefore, to obtain stationarity time, the collinearity measure was used in [18] in order to characterize the non-WSSUS typical of highway and urban scenarios. But, the collinearity measure falls short of taking the strict positivity of the LSF into account. Hence, in [19], the time and frequency divergences of the non-WSSUS vehicular channel at 5.2 GHz were characterized using spectral divergence measure. However, for wide bandwidth applications the LSF and CCF do not suffice since they are Doppler operator based and narrowband oriented; and the obtained coherence and stationarity parameters will vary with frequency for every single realization. And of course as stated earlier, the fast movement of paths from one delay bin to another suggests that the non-WSSUS model of narrowband channels may be different from that of the wideband channels. In [20], the concept of local regions of stationarity (LRS) of the mobile radio channel was presented and used to obtain nonstationary information on the power-delay profile of the channel. We note that this concept of LRS inspired the definition of the stationarity region adopted in this study.

Some of the existing studies on time-scale domain channel characterization are available in [4-10]. In [4], Weiss presented the use of wavelet theory in wideband correlation processing, and the importance of wideband processing in the wavelet (time-scale) domain. In [5,6], the use of the concepts from wavelet transforms and group theory to derive a linear time-varying system characterization for wideband input signal was presented. The canonical time-scale representation of the time-varying channel was proposed in [7]. In [8], the Mellin transform-based time-scale was applied to address the issue of joint-multipath scale diversity gain over dyadic time-scale framework. A similar work directed toward achieving joint scale-lag (delay) diversity in wideband mobile direct spread spectrum systems was presented by Margetts et al. [9]. In [10], the time-scale channel characterization was presented in the wavelet domain. However, while all these literatures projected the notion of time-varying channel characterization using the time scaling operator, the application of this method to actual channel parameterization was not discussed. More also, the authors of [4-10] did not address the issue of statistical channel characterization especially the case of non-WSSUS which is the main focus of this study.

## 3. System model

In general, for transmit signal $x(t)$ and received signal $y(t)$, the continuous time-scale and time-frequency representation of the linear time-varying (LTV) channel $\mathbf{H}$ are, respectively, given by

$$y(t) = \iint W_{\mathbf{H}}(\tau, s)\, a(t)\, x\left((t-\tau)/s\right)\, d\tau\, ds/s^2 \tag{3}$$

$$y(t) = \iint S_{\mathbf{H}}(\tau, \upsilon) a(t)\, x(t-\tau)\, e^{j2\pi\upsilon t} d\tau\, d\upsilon \tag{4}$$

where $a(t)$ is the amplitude. The terms $W_{\mathbf{H}}(\tau, s) = \int y(t)\, a(t)\, x\left((t-\tau)/s\right)\, dt$ and $S_{\mathbf{H}}(\tau, \upsilon) = \int h(\tau, t)\, e^{-j2\pi\upsilon t}\, dt$ denote the delay-scale (wideband) spreading function [8-10,21] and the delay-Doppler spreading function [21], respectively. While the latter is interpreted as the reflectivity of the scatterers associated to propagation delay $\tau$ and Doppler shift $\upsilon$, the former is interpreted as the reflectivity of the scatterers associated to delay $\tau$ and scale shift (or time scaling) $s$.

The scale $s = (c \pm \nu)/(c \mp \nu)$ is related to frequency by

$$s\{f_p\} = \{f_p\}(c \pm \nu)/(c \mp \nu), p = 1, 2, .., P. \tag{5}$$

The term $\{f_p\}$ in (5) is the frequency vector of length $P$ comprising stepwise of all the frequency components of the transmitted signal. Indeed, the pairs of Equations 3 and 4 are equivalent in some applications, but are not in some others. The distinction lies with the interaction between the transmit signal $x(t)$ and the channel $\mathbf{H}$. This interaction determines whether a system is narrowband or wideband.

The narrowband-wideband assumption is often made in two aspects: (1) the relationship between signal bandwidth $B_{\text{sig}}$ and coherence bandwidth $B_c$ [12]. (2) the relationship between $B_{\text{sig}}$ and $f_c$. In the first aspect, a general constraint $B_{sig} < <f_c$ is imposed, and the narrowband assumption is then upheld when the inequality $B_{\text{sig}} < B_c$ is satisfied, otherwise, the system under consideration is wideband. With the imposition of the constraint $B_{sig} < <f_c$, the pair of Equations 3 and 4 are equivalent and $W_{\mathbf{H}}(\tau, s) \equiv S_{\mathbf{H}}(\tau, \upsilon)$ irrespective of whether the system is wideband or narrowband in this context. In the second aspect which is the focus of this article, no constraint is imposed and narrowband assumption is then made when $(B_{sig}/f_c) < B_f$, where $B_f$ (typically 0.2), is called the fractional bandwidth [22,23], otherwise, the system is wideband. For the rest of this article, narrowband and wideband are referred to in the context of this second aspect.

For the narrowband assumption, $\{f_p\}$ can be approximated to $f_c$ in (5) so that time scaling is equivalent to Doppler shift and $W_{\mathbf{H}}(\tau, s) \equiv S_{\mathbf{H}}(\tau, \upsilon)$ is valid. In the case of wideband, this equivalence is invalid and $W_{\mathbf{H}}(\tau, s)$ is the appropriate valid channel response. Wireless communication systems like UWB [22,23] and UWA channels [24,25] are wideband in this context.

It can be seen from (3) that the time-scale representation establishes a one-to-one correspondence between the received signal and the delay-scale spreading function. This one-to-one correspondence allows one to read up condense parameters and useful features directly from the channel response. However in practice, such correspondence is not feasible due to the stochastic nature of the channel. In order to obtain condensed and useful parameters from this random process, some assumptions can be made in order to define an interval over which the randomness of the channel can be deemed to be statistically stationary. In view of that, let $\cup$ be the universal set of all stochastic processes, there exist the subsets of $\cup$ whose statistical properties vary with certain degrees in respect to the variations within some intervals $J_k$, $k = 1, 2, .., K$. If we define the partition $J_k$ as the countable collection of subintervals, then we can denote the interval for which some statistical properties of a process under observation are assumed to be stationary, as $J_{(\nu)}$. One of the popular statistical properties used in channel characterization is the mean and the ACF [1].

## 4. WSSUS characterization

*Definition 1:* A process is called wide-sense stationary (WSS) if it's first two moments are independent of absolute time $t$ on a defined interval $J_{(\nu)}$. Such process is delineated if there is some partition for which the expression $J_{(\nu)} = J_k$, $\forall k$ is valid and provides time independence with respect to the mean and ACF.

If we denote the observation interval in general by $J$, then from Definition 1, we can identify two different time instants, $t$ and $t'$ over which the WSS assumption is defined. Let $J_{(\nu)} = t'-t$, if we incorporated the US assumption into the model, then for two given scale instants $s \neq 0$ and $s' \neq 0$, the ACF depends only on $\Delta\tau = \tau' - \tau$ and $\Delta s = s'-s$. The ACF of the time-scale channel is then given by

$$\begin{aligned} R_{W,wssus}(\tau, s, \Delta\tau, \Delta s) &= \mathrm{E}[W_{\mathbf{H}}(\tau, s)\, W_{\mathbf{H}}{}^*(\tau', s')] \\ &= \mathrm{E}[W_{\mathrm{H}}(\tau, s)\, W_{\mathrm{H}}{}^*(\Delta\tau + \tau, \Delta s + s)] \end{aligned} \tag{6}$$

In (6), '*' denotes conjugation and $\mathbf{E}[.]$ is the expectation operator. However, for simplicity we assume that $x(t)$ is real so that for the rest of this article, the conjugation '*' can be neglected. Hence,

$$\begin{aligned} R_{W,wssus}(\tau, s, \Delta\tau, \Delta s) = \mathrm{E}\Bigg\{ \int\int & \left[y(t)\, y(\Delta t)\right] \left[a(t) a(\Delta t)\right] \\ & \cdot \left[ x\left(\frac{t-\tau}{s}\right) x\left(\frac{\Delta t - \Delta\tau - \tau}{\Delta s + s}\right)\right] dt\, d\Delta t \Bigg\} \end{aligned} \tag{7}$$

It can easily be shown that

$$R_{W,wssus}(\tau, s, \Delta\tau, \Delta s) = \int R_{\gamma}(\Delta t) a(\Delta t)\, x\left(\frac{\Delta t - \Delta\tau - \tau}{\Delta s + s}\right) d\Delta t. \int \delta(t)\, a(t) x\left(\frac{t-\tau}{s}\right) dt = \left\langle R_{\gamma}, X^{(\tau,s)}_{\Delta\tau,\Delta s}\right\rangle_{\Delta t} \left\langle \delta, X^{(\tau,s)}\right\rangle_{t} \quad (8)$$

where

$X^{(\tau,s)}_{\Delta\tau,\Delta s} = a(\Delta t)\, x\left(\frac{\Delta t - \Delta\tau - \tau}{\Delta s + s}\right)$, and $X^{(\tau,s)} = a(t) x\left(\frac{t-\tau}{s}\right)$.

The first inner product on the right-hand-side (RHS) of (8) is called the *delay-scale scattering function* (DSSF)

$$\boldsymbol{P}_{wssus}(\tau, s) = \left\langle R_{\gamma}, X^{(\tau,s)}_{\Delta\tau,\Delta s}\right\rangle_{\Delta t} \quad (9)$$

The inner product $\left\langle \delta, X^{(\tau,s)}\right\rangle_{t}$ is an approximation of $\delta(\Delta\, \tau)\delta(\Delta s)$ which implies that at each different delay the distribution is simply a scaled version of the transmitted signal. The function $\boldsymbol{P}_{wssus}(\tau, s)$ has compact support defined on the set $\eta = \{s_{\min} \le s \le s_{\max}, \tau_{\min} \le \tau \le \tau_{\max}\}$ where $s_{\min}$ and $s_{\max}$ are the minimum and maximum scale spreads, respectively, and, $\tau_{\min}$ and $\tau_{\max}$ are the minimum and maximum delay spreads, respectively.

Equation 9 is comparable to the delay-Doppler scattering function $\boldsymbol{S}_{\mathbf{H}}(\tau, \upsilon) = \int R_{\mathbf{H}}(\Delta t, \tau)\, e^{-j2\pi\upsilon\Delta t} d\Delta t$, where $R_{\mathbf{H}}(\Delta t, \tau) \equiv \prod(R_{y}(\Delta t))$ is the delay cross-power density. The term $\prod$ is a filter or window operator whose output is dependent on the particular filter, $|\tau|$ and $x(t)$. The conventional WSSUS condensed parameters [12] like the coherence bandwidth $B_{c}$ and coherence time $T_{c}$ can be used to quantify the channel dispersion bearing in mind the relation between frequency and scale as stated in (5). While the delay spread/$B_{c}$ in both $\boldsymbol{S}_{\mathbf{H}}(\tau, \upsilon)$ and $\boldsymbol{P}_{wssus}(\tau, s)$ are equivalent, their similarity in terms of frequency spread/$T_{c}$ is derivable from the inverse relation between frequency and scale [4]. Thus, it suffices that $\boldsymbol{S}_{\mathbf{H}}(\tau, \upsilon) \equiv \Lambda^{-}(\boldsymbol{P}_{LSSUS}(\tau, s))$ where $\Lambda^{-}$ is the scale-to-Doppler conversion operator. This implies that while the computation of $\boldsymbol{S}_{\mathbf{H}}(\tau, \upsilon)$ is dependent on the carrier frequency, the realization of $\boldsymbol{P}_{wssus}(\tau, s)$ is independent of the carrier frequency or any reference frequency. Therefore, different values of $T_{c}$ can be obtained for different values of frequencies, from a single $\boldsymbol{P}_{wssus}(\tau, s)$ realization. The variation of coherence time with frequency is depicted in Figure 1 for a typical wideband channel at a reference mobile speed of 5 m/s. This figure shows that $T_{c}$ computed at $f_{c}$ vary significantly with $T_{c}$ at other frequencies within a defined wide bandwidth.

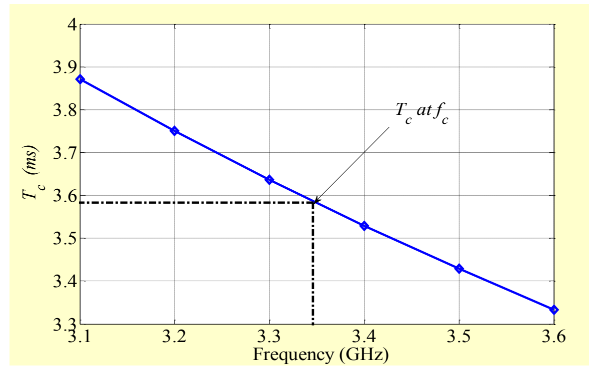


**Figure 1 Variation of coherence time with frequency.**

## 5. Non-WSSUS characterization

*Definition 2*: A process is called local-sense stationary (LSS) if there exist some partitions for which at least one interval say $J_{i}$ is considered to be WSS, $J_{(\nu)} = J_{i}$. Within this 'locally' stationary interval $J_{i}$ the second-order statistics are approximately independent of time, but vary slowly in time across all other intervals for which $J_{(\nu)} \neq J_{k \neq i}$. Thus, the autocorrelation is WSS at $J_{i}$ but non-WSS at all other intervals $J_{k} \neq J_{i}$.

For all other processes with gross time varying statistical properties over all $J$ for which no $J_{(\nu)}$ can be ascertained for practical purposes, the nonstationary process is defined.

Definition 2 is related to that of the locally stationary random processes introduced by Silverman [26], and the uniformly bounded linearly stationary (u.b.l.s) processes introduced by Tjøstheim and Thomas [27]. As it was pointed out in [27], the above definition is the same as saying that the u.b.l.s processes can be obtained by filtering WSS processes. Hence, the LSS process has the desirable property of including WSS process as a special case.

The relation among the various subsets of the statistical processes is shown in Figure 2. Thus, a little above the upper bound of strict-sense stationarity lies the quasi-stationary region and a little below the lower bound of non-stationarity lies the quasi-nonstationary region.

From Definition 2, we can identify three different time instants, $t$, $t'$, and $t''$ over which the LSS assumption is defined. Within the quasi-stationary intervals for two time instants $t$ and $t'$, the second-order channel statistics are constant over $\Delta t = |t'-t|$. However, the statistics vary across the quasi-nonstationary interval $J = |t''-t|$ over which LSS is defined. If we extend the above statements to the concept of uncorrelated scattering (US), then it can easily be shown that, $t''-t = \Delta(t + \Delta t) + \Delta t$, $\Delta s = |s'-$

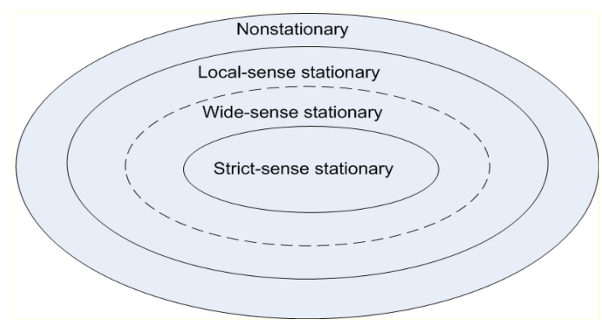


**Figure 2** **Relation among the various subsets of the stationary processes**.

$s|$, $s''$-$s$ = $\Delta(s + \Delta s)$+ $\Delta s$, $\Delta\ \tau = |\ \tau'$- $\tau|$ and $\tau''$- $\tau = \Delta\ (\tau + \Delta\tau) + \Delta\tau$. Therefore, the ACF for the LSSUS is given for some spatial displacement $\Delta\vec{r}$ by

$$R_{W,LSSUS}(\tau, s, \Delta\tau, \Delta s; \Delta\vec{r}) = \mathrm{E}[W(\tau, s)\ W^{*}(\tau'', s'')] \quad (10)$$

$$= \mathrm{E}[W(\tau, s)\ W^{*}(\Delta(\tau + \Delta\tau) \\ . + \Delta\tau + \tau, \Delta(s + \Delta s) + \Delta s + s)] \quad (11)$$

With the assumption of a real $x(t)$ it can easily be shown that

$$R_{W,LSSUS}(\tau, s, \Delta\tau, \Delta s; \Delta\vec{r}) = \left\langle R_{\gamma}, .X^{(\tau,s)}_{\Delta(\tau+\Delta\tau)+\Delta\tau,\Delta(s+\Delta s)+\Delta s} \right\rangle_{\Delta(t+\Delta t)+\Delta t} \left\langle \delta, X^{(\tau,s)} \right\rangle_{t} \quad (12)$$

where $X^{(\tau,s)}_{\Delta(\tau+\Delta\tau)+\Delta\tau,\Delta(s+\Delta s)+\Delta s} = a(\Delta(t + \Delta t) + \Delta t + t)$
$. x\left(\frac{(\Delta(t + \Delta t) + \Delta t + t) - (\Delta(\tau + \Delta\tau) + \Delta\tau + \tau)}{\Delta(s + \Delta s) + \Delta s + s}\right)$
and $X^{(\tau,s)} = a(t)x\left(\frac{t - \tau}{s}\right)$.

The first inner product term in (9) is called the *local-sense scattering function* (LSSF):

$$\boldsymbol{P}_{LSSUS}(\tau, s) = \left\langle R_{\gamma}, X^{(\tau,s)}_{\Delta(\tau+\Delta\tau)+\Delta\tau,\Delta(s+\Delta s)+\Delta s} \right\rangle_{\Delta(t+\Delta t)+\Delta t} \quad (13)$$

The scattering function $\boldsymbol{P}_{LSSUS}(\tau, s, \Delta\tau, \Delta s)$ completely characterizes the LSSUS channel. In relation to (8), there exist some $\Gamma > 0$ such that

$$\left\| \left\langle R_{\gamma}, X^{(\tau,s)}_{\Delta\tau,\Delta s} \right\rangle_{\Delta t} \right\|^{2} \leq \Gamma \left\| \left\langle R_{\gamma}, X^{(\tau,s)}_{\Delta(\tau+\Delta\tau)+\Delta\tau,\Delta(s+\Delta s)+\Delta s} \right\rangle_{\Delta(t+\Delta t)+\Delta t} \right\|^{2} \quad (14)$$

Implicitly for small values of spatial displacement $\Delta\vec{r}$ the terms $\Delta(t + \Delta t)$, $\Delta(s + \Delta s)$, and $\Delta(\tau + \Delta\tau)$ in (8) become insignificant, $\Gamma = 1$, and (13) simplifies to (9)

$$\boldsymbol{P}_{wssus}(\tau, s) = \boldsymbol{P}_{LSSUS}(\tau, s)\big|_{\Delta t,\Delta\tau,\Delta s\to 0} \\ = \left\langle R_{\gamma}, X^{(\tau,s)}_{\Delta\tau,\Delta s} \right\rangle_{\Delta t} \quad (15)$$

Therefore, the measure of the channel stationarity or nonstationarity is with regard to the extent to which $\boldsymbol{P}_{LSSUS}(\tau, s)$ deviates from $\boldsymbol{P}_{wssus}(\tau, s)$.

## 6. Estimation of stationarity degree

### 6.1. Stationarity test

The LSSUS scattering function(s) completely characterizes the wireless wideband channel. Let $\Psi = \left\{ \boldsymbol{P}_{LSSUS}(\tau, s)_{\theta} : \theta \in \Theta \subset \Re \right\}$ denote the set of all LSSUS scattering functions for a particular case where $\boldsymbol{P}_{wssus}(\tau, s)$ is a subset. The main issue is how to estimate the deviation of the set $\Psi$ from its subset $\boldsymbol{P}_{wssus}(\tau, s)$. Though there are several proposed methods in the literature for modeling locally stationary processes, the problem of testing the stationarity of such processes has attracted less attention in the literature. Some existing work in stationarity test can be found in [28,29]. The weaknesses of some of the test module proposed in literature include the dependency of the test on the choice of the regularization parameter [28], and the complexity of the solutions [29]. In [14], a simplified alternative method for measuring deviation from stationarity in locally stationary processes was presented. This method measures stationarity degree by the best $L^2$ approximation of the spectral density of the underlying process by the spectral density of a stationary process. Hence, using the minimal distance deviation measure proposed in [14] we define the stationarity measure $\Xi^{2}_{\tau,s}$ as the measure of the deviation of $\boldsymbol{P}_{LSSUS}(\tau, s)$ from $\boldsymbol{P}_{wssus}(\tau, s)$:

$$\Xi^{2}_{\tau,s} = \min_{P_{wssus}} \iint \left(\boldsymbol{P}_{LSSUS}(\tau, s) - \boldsymbol{P}_{wssus}(\tau, s)\right)^{2} \frac{d\tau ds}{s^{2}} \quad (16)$$

with the limit of integration practically taken over $[s_{\min}\ s_{\max}]$ and $[\tau_{\min}\ \tau_{\max}]$. The term $\Xi^{2}_{\tau,s}$ is a measure of the deviation of $\boldsymbol{P}_{LSSUS}(\tau, s)$ from $\boldsymbol{P}_{wssus}(\tau, s)$.

### 6.2. Non-WSSUS condensed channel parameters

As stated earlier, wireless channels are often characterized using the condensed parameters, $B_c$ and $T_c$. However, these parameters do not completely characterize all classes of time-varying processes. It should be noted that coherency is a concept developed for WSSUS channels to describe their nonselectivity [12]. In this sense, the stationarity attribute of the WSSUS channel is infinite. Thus, the channel is nonselective (coherence) in time and frequency over certain bounded values, and is assumed to remain statistically invariant (stationary) in time and frequency for infinite extent determined by the choice of the interval of observation. Therefore, apart from the coherence parameters, the stationarity parameters [2] are also required in order to fully characterize the LSSUS channel.

In [2], the stationarity parameters were introduced and obtained as the inverse of some normalized weighted integrals which defines the spread of the CCF. The weight function is a function of the spread in time, frequency, Doppler, and delay. In this study, we opt for a different approach to obtain the stationarity parameters. To do so, we consider the stationarity parameters as quantifying the deviation of the LSSUS from WSSUS. In consonance with (13), we can define the minimal delay profile deviation (MDPD) $\Xi_\tau^2$ and the minimal scale profile deviation $\Xi_s^2$ by

$$\Xi_\tau^2 = \min_{P_{wssus}} \iint \left(P_{LSSUS}(\tau, s) - P_{wssus}(\tau, s)\right)^2 \frac{ds}{s^2} \tag{17}$$

$$\Xi_s^2 = \min_{P_{wssus}} \iint \left(P_{LSSUS}(\tau, s) - P_{wssus}(\tau, s)\right)^2 d\tau \tag{18}$$

The minimal r.m.s delay spread deviation $\Delta\tau_{rms}$ and minimal scale spread deviation $\Delta s_{rms}$ are given by

$$\Delta\tau_{rms} = \left(\frac{\int \left(\Xi_{\tau,LSSUS}^2\ \tau^2 - \Xi_\tau^2\ \tau^2\right) d\tau}{\int \Xi_{\tau,LSSUS}^2 d\tau} - \left(\frac{\int \left(\Xi_{\tau,LSSUS}\ \tau - \Xi_\tau\ \tau\right) d\tau}{\int \Xi_{\tau,LSSUS}^2 d\tau}\right)^2\right)^{1/2} - \cdot\left(\frac{\int \left(\Xi_{\tau,wssus}^2\ \tau^2 - \Xi_\tau^2\ \tau^2\right) d\tau}{\int \Xi_{\tau,wssus}^2 d\tau} - \left(\frac{\int \left(\Xi_{\tau,wssus}\ \tau - \Xi_\tau\ \tau\right) d\tau}{\int \Xi_{\tau,wssus}^2 d\tau}\right)^2\right)^{1/2} \tag{19}$$

and

$$\Delta s_{\max} = s_{\max,LSSUS} - s_{\max.wssus} \tag{20}$$

where

$$\Xi_{\tau,wssus}^2 = \min_{P_{wssus}} \iint \left(P_{LSSUS}(\tau, s) - P_{wssus}(\tau, s)\right)^2 \frac{ds}{s^2}\bigg|_{P_{LSSUS}(\tau,s)=0}$$

and

$$\Xi_{\tau,LSSUS}^2 = \iint \left(P_{LSSUS}(\tau, s) - P_{wssus}(\tau, s)\right)^2 \frac{ds}{s^2}\bigg|_{WSSUS(\tau,s)=0}$$

Hence, the stationarity bandwidth $B_s \approx 1/\Delta\tau_{rms}$, stationarity time $T_s \approx 1/\Delta s_{rms}$ $\{f_p\}$, coherence bandwidth $B_c$ and coherence time $T_c$ provide complete parameterization of the LSSUS channel. The stationarity parameters tend to infinity in the case of WSSUS for which $\{\Delta\tau_{rms}, \Delta s_{rms}\} \rightarrow 0$. It can also be seen that using this approach, different values of $T_s$ can be obtained from a single wideband channel realization for different values of frequencies.

It is important to note the use of $\Delta\tau_{\max}$ in [2] in defining the stationarity bandwidth. The parameter $\tau_{\max}$ is a singular value whose statistics across different channel realizations are independent of other delay values in a particular channel response. On the other hand, the parameter $\tau_{\text{rms}}$ is obtained taking into consideration the statistics of all the delay values associated with a particular channel response. Hence, while $\Delta\tau_{\max}$ may be appropriate value for determining the channel coherence parameters, it is not quite suitable for the statistical measure of stationarity. For instance, let us consider two channel responses $h_1(\tau, t)$ and $h_2(\tau, t)$ at two different time instants as shown in Figure 3.

From Figure 3, it can be seen that $\tau_{\max}$ is the same for both $h_1(\tau, t)$ and $h_2(\tau, t)$, hence $\Delta\tau_{\max}$ is zeros. But it is obvious that both responses are not equivalent, in this case we do not know for how much they deviate from each other using the information provided by $\Delta\tau_{\max} = 0$. On the other hand $\Delta\tau_{rms} \neq 0$ hence, some value of the statistical deviation of $h_1(\tau, t)$ from $h_2(\tau, t)$ is readily available as it is truly the case in this example. For instance, the employment of multipath diversity means that $h_1(\tau, t)$ provides better channel diversity than $h_2(\tau, t)$ since it offers more fingers.

### 6.3. Stationarity distance

An important issue in the characterization of the LSSUS is how to determine the interval $T_{(\nu)}$ over which WSSUS is defined. This interval depends basically on the spatial displacement $\Delta\vec{r}$ and terminal velocity $\nu$. Let the displacement at a time instant $t$ be given by $\vec{r}(t') - \vec{r}(t) = \Delta\vec{r}$, where $t'$ is some instantaneous time. For a terminal velocity $\nu$, $\Delta\vec{r} = J.\nu$. The WSSUS assumption requires that $\Delta\vec{r}$ must be small enough to ensure statistical stationarity. Succinctly, $J = |t'-t|$ should not exceed some time interval $J_{(\nu)} = |t'-t|$, where $t_\nu'$ is a

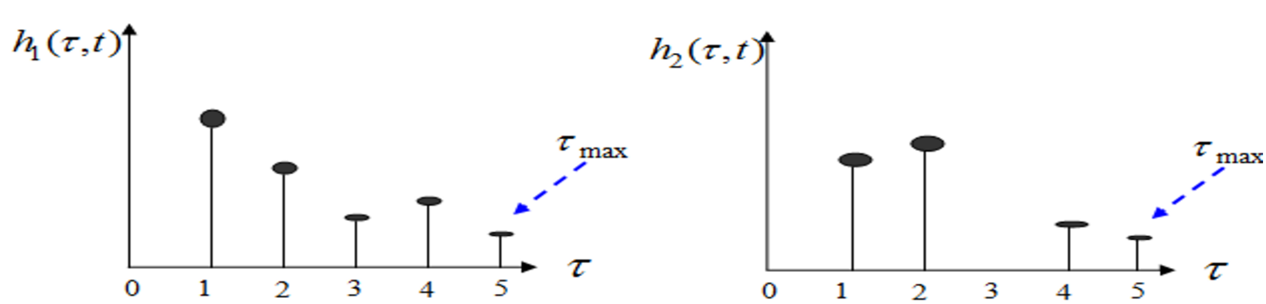


**Figure 3 Channel responses $h_1(\tau, t)$ and $h_2(\tau, t)$ at two different time instants**.

time instant within which statistical stationarity is guaranteed. In order to determine $J_{(\nu)}$, consider the fact that the channel response to any excitation can be seen as a 'snapshot' of the channel. To adequately account for changes in the channel, these snapshots need to be taken sufficiently often at some intervals called the repetition duration $T_{\text{rep}}$. The repetition duration encompasses the interval $J$, and some time $t_{\text{ps}}$ for data processing and storage. Intuitively, $J_{(\nu)}$ should be smaller than the time duration $T_{\Delta}$ over which the channel changes, $J_{(\nu)} < T_{\Delta}$. There exists a minimum sampling rate required to be able to identify a time-variant process with a band-limited spectrum. The temporal sampling frequency must be twice the maximum frequency shift $\upsilon_{\max}$ [12]. Thus, we can express the interval $J_{(\nu)}$ as

$$J_{(\nu)} \leq \frac{\chi c}{2 f_{up} \nu} \tag{21}$$

where $\nu_{\max}$ is the maximum constant velocity of the mobile unit, $f_{\text{up}}$ is the upper band frequency, and $\chi$ is arbitrarily chosen to ensure that a reasonable measurement/sampling distance is obtained. The value of $\chi$ must be carefully chosen to ensure that the $J_{(\nu)}$ is not too small (to ensure reasonable acquisition time) nor too big (as to violate stationarity condition). The corresponding stationarity distance $\Delta \vec{r} = X_s$ is given by

$$X_s \leq J_{(\nu)} \nu \tag{22}$$

## 7. Application relevance of LSSUS assumption

The practical illustrations of the LSSUS concept that stem directly from physical considerations in typical communication scenarios are presented in this section. In essence, the LSSUS scattering functions can be viewed as a set of evolutionary functions that are more or less the instantaneous responses of the channel to an input. Although the coherence parameters of these instantaneous channel realizations vary from one to another, for practical rationality we consider channel coherency only with respect to the reference channels response taken to be WSSSU. Hence, all other sets of $\Psi = \left\{ P_{LSSUS}(\tau, s)_{\theta} : \theta \in \Theta \subset \Re \right\}$ are defined only by the stationarity parameters.

While statistical stationarity are desired in order to achieve simple transceiver designs, the knowledge of statistical nonstationarity can also be employed to improve the performance of the transceiver. For instance, nonstationarity information can give insight into the long-term behavior of the system in terms of channel estimation/prediction, ergodic capacity, and diversity. Hence, the joint knowledge of stationarity and coherence parameters can be used to access the long-term behavior of the channel and adjust the transceiver parameters. In [2], brief discussion on the relevance of non-WSSUS characterization on ergodic capacity assumption was presented, and further application potential to delay-Doppler diversity was mentioned. In this study, we provide broad-based formulation of the application relevance of LSSUS to ergodic channel capacity assumption, time diversity, frequency diversity, joint time-frequency diversity, and delay-Doppler/delay-scale diversity.

Let us consider the case of the doubly spread flat-fading channel with time-frequency coherence/stationarity subspace as shown in Figure 4. If we assumed that independent and identically distributed (i.i.d) channel realizations occur every $T_c$ second for the corresponding $B_c$, then averaging over $T_s = NT_c$, $B_s = KB_c$, $\{n, k\} = 1, 2, 3..$, $\{N, K\}$, $\{N, K\} \to \infty$ gives a convergent value. The number of i.i.d channel realizations $\aleph$ can be given by [2]

$$\aleph = \left| \frac{T_s B_s}{T_c B_c} \right| \tag{23}$$

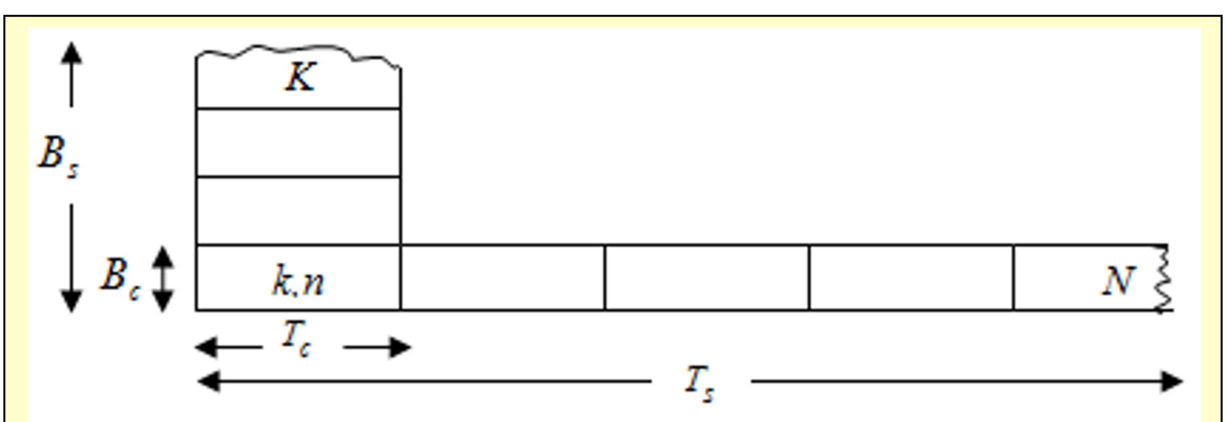


**Figure 4** Time-frequency coherence and stationarity subspaces over doubly spread channel.

Thus, the stationarity dimension $T_s \times B_s$ determines the number of effective i.i.ds available for a given channel with respect to the coherence dimension $T_c \times B_c$. We will show that the value of $\aleph$ determines the validity of ergodic assumptions. And it also affects the effective time-frequency diversity order of a given time-varying channel.

### 7.1. Ergodic capacity

The ergodic capacity $\boldsymbol{C_{erg}}$ of the channel is often desired in order to reveal the 'long-term' properties of an arbitrary fading process say $\chi(t, \tau)$ which is assumed to be an ergodic process in $t$. It is well known that in order to achieve ergodic capacity, averaging by coding over numerous i.i.d. fades is required [30]. Thus, whether sufficient averaging can be achieved to guarantee ergodic capacity depends on the number of i.i.d fading coefficients offered by the channel. The channel capacity $\boldsymbol{C}$ in the case where the channel state information is available to the receiver can be expressed as [30]

$$\mathrm{C} = \mathrm{E}\left[\int \log_2\left(1 + \frac{P_{av}|\chi(t,f)|^2}{N_0}\right)df\right] \tag{24}$$

where $P_{av}$ is the average power, $N_0$ is the noise variance, and $\chi(t, f)$ is the response of the channel, and by analogy $\chi(t, f) \equiv \boldsymbol{W}(\tau, s)$ in the time-scale domain.

Under the ergodic assumption, the statistics of $\chi$ are independent of either $t$ or $f$ in $\chi(t, f)$ and subsequently $\tau$ or $s$ in $\boldsymbol{W}(\tau, s)$. If $P_{\mathrm{av}}$ is nonnegative, then the relation

$$\mathrm{C} = \int \mathrm{E}\left[\log_2\left(1 + \frac{P_{av}|\chi(t,f)|^2}{N_0}\right)\right]df \tag{25}$$

holds.

As defined by the LSSUS statistics, the time and scale independency of the statistics of $\boldsymbol{W}(\tau, s)$ are accessed over the stationarity dimension. Therefore, for flat-fading, the $\aleph$ -dependent ergodic capacity can then be given by

$$\boldsymbol{C_{erg}} = \aleph \to \infty \, \frac{1}{\aleph} \sum_{\aleph} \left(\log_2\left(1 + \boldsymbol{q}_{\aleph}\right) \, p_{\aleph}(\boldsymbol{q})\right) \tag{26}$$

where $\boldsymbol{q}_{\aleph} = \dfrac{P_{av}. \left[|\chi_{\aleph}(t,f)|^2\right]}{N_0}$, with probability distribution $p_{\wp}(\boldsymbol{q})$.

The expression (26) implies that when $B_s T_s \to \infty$ (WSSUS case), the number of independent realizations is large enough and ergodic capacity is achieved. However, as $T_s$ decreases the number of i.i.ds reduces and the ergodic capacity can only be defined for sufficiently large realizations. In the case where there is insufficient number of i.i.ds, the use of $\mathbf{C}_{\mathrm{erg}}$ as a measure of channel capacity becomes unreliable.

### 7.2. Effective diversity

Diversity techniques are often employed to combat the fading effect of the channel. The basic idea is to transmit the signal over multiple i.i.d channels, while keeping the total power constant by transmitting at a lower power in each channel [31]. It is evident that diversity performance improves monotonically with increasing number of i.i.d [32]. In fact as the number of i.i.d $\aleph$ approaches infinity, the performance of coherent diversity reception converges to the performance over a non-fading AWGN channel [33-37]. In practice, diversity is physically implemented in a variety of ways such as time diversity, frequency diversity, joint time-frequency diversity, delay diversity, Doppler diversity, scale diversity, joint delay-Doppler diversity, and joint delay-scale diversity. In the case of time, frequency, and joint time-frequency diversities, decoupling the stationarity dimension and (23) gives the number of effective diversity order $d_{.}$ as

$$d_{TD} = \aleph_T = \frac{T_s}{T_c} \qquad \to \text{Time diversity} \tag{27}$$

$$d_{FD} = \aleph_F = \frac{B_s}{B_c} \qquad \to \text{Frequency diversity} \tag{28}$$

$$d_{TFD} = \aleph = \frac{T_s B_s}{T_c B_c} \qquad \to \text{Time} - \text{frequency diversity} \tag{29}$$

Thus, as the stationarity dimension changes (by virtue of the variation in the degree of the correlation among channel realizations at different time instants), the diversity order varies too. Hence, the stationarity dimension sets an upper limit for the above diversity schemes.

The above relationships can be extended to the case of delay-Doppler diversity [32] and that of the delay-scale diversity [8,9]. In order to do this, it should be noted that time-frequency/scale coherence dimension is inversely related to the delay-Doppler/scale diversity in the doubly spread channel. Let us consider the case of delay-Doppler diversity [32]. The number of delay diversity and Doppler diversity branches depends on the maximum delay spread and maximum Doppler spread, respectively. Since these parameters vary by virtue of LSSUS assumption, it means that the achievable effective delay/Doppler diversity should also vary with time. We restrict our analysis in this article to delay-Doppler diversity.

## 8. Illustrative measurements and simulation

In this section, illustrative measurement and simulation examples for the time-varying UWB channel typical of the infostation [15] environments are provided. This environment depicts a typical scenario where the time-scale domain LSSUS channel suffices. The concept of infostation [15-17] illustrated in Figure 5 presents a new way to look at the problem of providing high data rate wireless access. It is an isolated pocket area with small coverage (about 100 m) of high bandwidth connectivity that collects information requests from mobile users and delivers data while users are going through the coverage area. One of the technologies that have the potential to deliver the envisaged high-data rate infostation services is the UWB signalling [17].

Most existing UWB channel characterization and measurement have been limited to the case where the channel is assumed to be fixed over the transmission duration [38-41]. However, for many infostation channels, time variation is expected due to the mobility of one of the communication terminals. In this case, the WSSUS assumption and the assumption of uniform Doppler shift across the operating bandwidth all composite frequencies are no more valid. In the illustrative measurement and simulation below, we consider the LSSUS analysis with respect to both time and frequency dispersive effects.

### 8.1. Illustrative measurement

The complex channel response is measured with a vector analyzer (VNA) R&S® ZVL13. Measurements were carried out at various locations along a road within the vicinity of Wireless Communication Centre (WCC) complex, Universiti Teknologi Malaysia, as shown in Figure 6 for the frequency range 3.1-3.6 GHz. The speed of the mobile is about 2 m/s, and measurements were taken at each location marked $A_1$-$A_6$. At each location, the measurement is repeated 50 times. The VNA records the variation of 601 complex tones within the band. This recording is done by sweeping the spectrum in about $J_v$ time interval. The time $J_v$ is obtained from (21) where $\chi$ is taken to be 20. Apart from the mobile antenna, all the objects (potential scatterers) are kept stationary throughout the duration of the measurement. The antennas (monopoles) are of the same height, 1.5 m and the transmit power is -10 dB for all measurements. The signal from the receiving antenna is passed through a low noise amplifier with a gain of 20 dB. The distances between the locations are $A_1$-$A_2$ = 1 m, $A_2$-$A_3$ = 1 m, $A_3$-$A_4$ = 4 m, $A_4$-$A_5$ = 3 m, and $A_5$-$A_6$ = 3 m. The distances between the infostation antenna and the mobile antenna at locations $A_1$, $A_2$, $A_3$, $A_4$, $A_5$, and $A_6$ are 6, 5.7, 5.4, 5, 5.5, and 6 m, respectively.

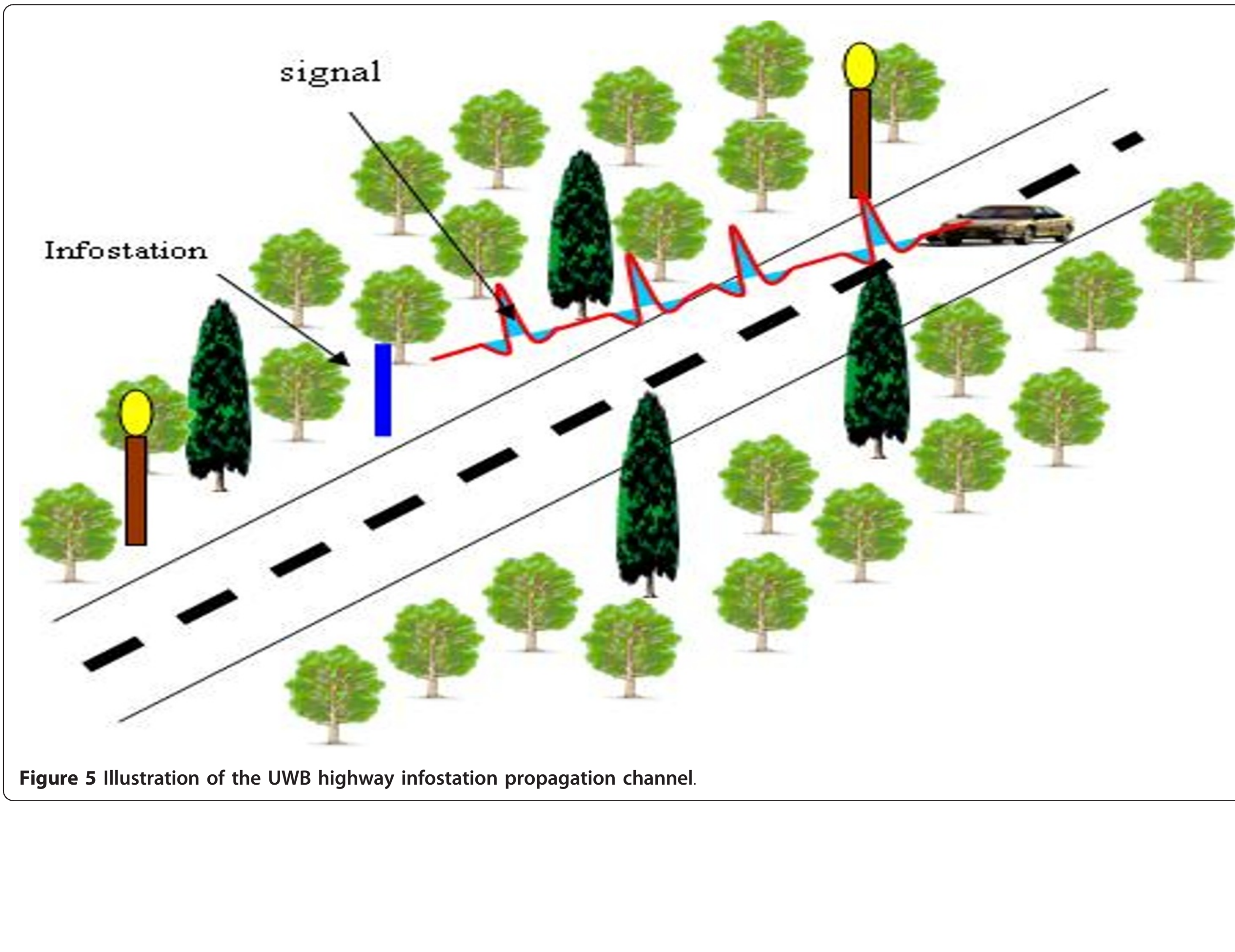


**Figure 5** Illustration of the UWB highway infostation propagation channel.

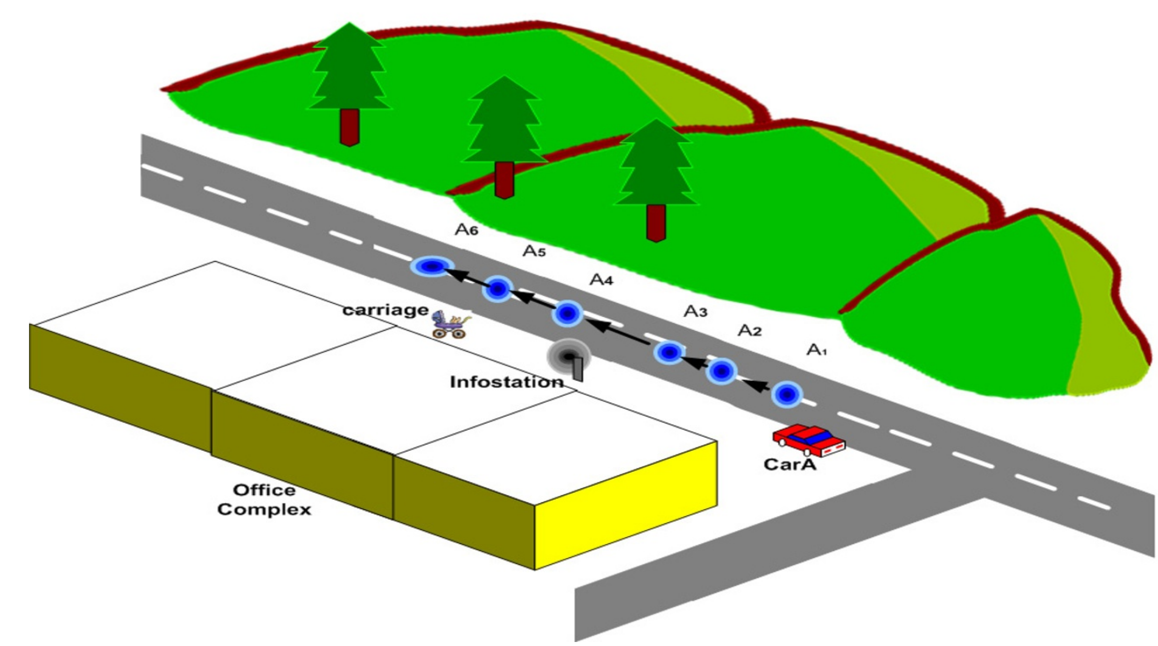


**Figure 6** Illustration of the measured propagation environment.

In order to obtain the statistical model of the time-variant response from the measured complex channel responses, we apply the autoregressive (AR) model proposed in [42]. Let $H(f_p, t; A)$ be the time-varying complex transfer function measured at a location $A$ and time $t$. Then the first- and second-order statistics of the measured channel are captured by the model

$$H(f_p, t; A) = \sum_{n=1}^{N} a_n \, H(f_{p-n}, t; A) + V(f_p) \qquad (30)$$

where $V(f_p)$ is a complex white noise process and $a_n$ is the function representing the $n$th time-varying AR coefficient. The MDPD for the positions $A_2$, $A_3$, $A_4$, $A_5$, and $A_6$ (with reference to $A_1$) are shown in Figure 7.

The computed $B_s$ for the positions $A_2$, $A_3$, $A_4$, $A_5$, and $A_6$ are approximately 12, 3.32, 0.56, 0.77, and 0.29 GHz, respectively. These $B_s$ values are computed at -30 dB threshold. For this same threshold $B_c$ value of 23.2 MHz is obtained using the WSSUS scattering function (9) at reference position $A_1$. The implication of the ratio $B_s/B_c$ can be observed in the case of multiband orthogonal frequency division multiplex (MB-OFDM) UWB in this channel. If we consider the MB-OFDM system designed with $N_s$ number of subcarriers and subcarrier spacing of $F_s$ MHz. In order to combat fading in MB-OFDM, the bandwidths of the subcarriers should be equal or less than the $B_c$ to ensure flat-fading. However, the choice of small value for $F_s$ implies that the system will be more susceptible to inter-carrier interference (ICI) [43]. Hence, the choice of the value of $F_s$ should be optimal between combating frequency selective fading and ICI. If we consider a total bandwidth of 528 MHz, the value of $F_s$ for 128, 64, 32, and 16 subcarriers are 4.125, 8.25, 16.5, and 33 MHz, respectively. Hence, the choice of 128 subcarrier ensures good ISI performance but with increased error due to ICI, and the choice of 16 subcarriers ensures good ICI performance but with increased susceptibility to ICI. The optimal choice will be to choose the number of subcarriers such that $kF_s = B_c$, where the value of $k$ should be chosen to take care of the time-varying nature of $B_c$. Conventionally, $k$ is chosen to be fixed and of low value, hence a fixed number of subcarriers. The signal-to-noise ratio (SNR) degradation caused by ICI is given by [44]

$$D \cong \frac{10}{\ln 10} \frac{1}{3} \left( \frac{\pi f_e}{F_s} \right)^2 \left( 1 + \frac{E_s}{N_0} \right) \qquad (31)$$

where $f_e$ is the frequency offset. If we consider the above channel measurement, then the SNR degradations for 128, 64, 32, and 22 subcarriers are shown in Figure 8.

Figure 8 shows that the SNR degradation for 22 subcarriers ($k = 1$) is better than the performance at $k < 1$ (128, 64, and 32 subcarriers). However, when $k$ is greater than unity, ISI degradation sets in. This implies that instead of a fixed value for $k$, some form of adaptive subcarrier bandwidth can be employed. The value of

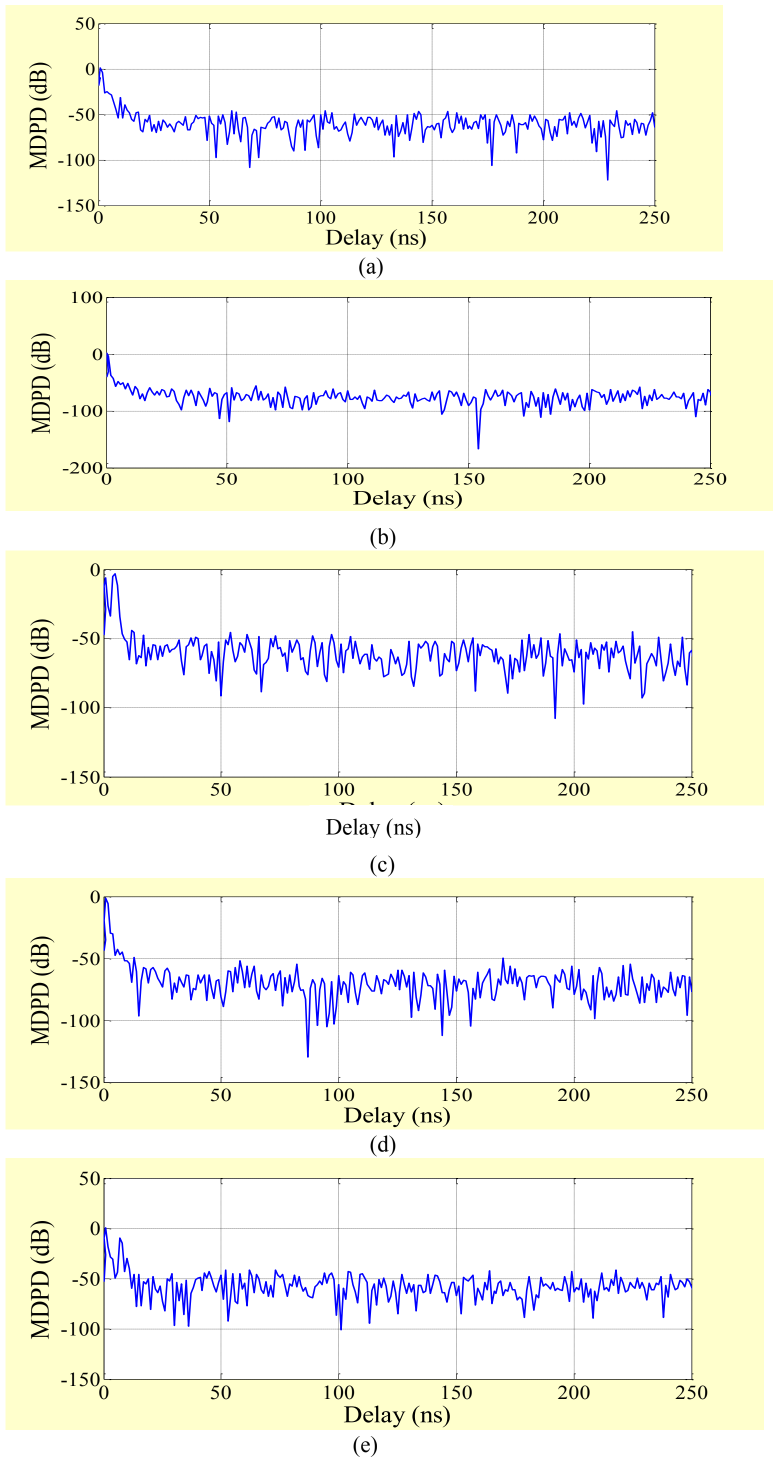


**Figure 7 MDPD at position: (a) $A_2$, (b) $A_3$, (c) $A_4$, (d) $A_5$, and (e) $A_6$.**

stationarity bandwidth can provide information that can be used to adjust $k$ for optimal performance. The values of $B_s/B_c$ at $A_1$, $A_2$, $A_3$, $A_4$, $A_5$, and $A_6$ are approximately, ∞, -538, -143, 23, -33, and 12, respectively. We can define the time/bandwidth utilization parameter $U^{(\Im)}$ by

$$U^{(\Im)} \cong -B_{co}^{-1}\left(\frac{\Im B_{co}}{\Im - 1} - B_{co}\right), \Im \in \{\Im_{TF}, \Im_F, \Im_T\} \quad (32)$$

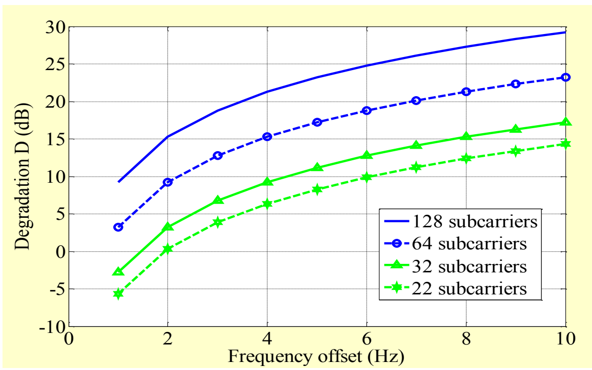


**Figure 8** SNR degradation as a function of subcarrier spacing.

where $\Im_{TF} = (B_s T_s)/(B_c T_c)$, $\Im_F = B_s/B_c$, $\Im_T = T_s/T_c$ and $B_{co}$ is the reference coherence bandwidth. Hence, the values of $U^{(\Im_F)}$ at $A_1$, $A_2$, $A_3$, $A_4$, $A_5$, and $A_6$ are approximately, 0, 0.19, 0.7, -4.6, 3.13, and -9.1%, respectively. The negative sign in $U^{(\Im_F)}$ indicates that k is greater than 1 by the given percentage and the positive sign in $U^{(\Im_F)}$ indicates that $k$ is less than 1 by the given percentage. Therefore, this nonstationarity information can be employed to adjust the values of $k$ in order to optimize the system performance at any time instant.

Since the velocity of the mobile is constant throughout the measurement run, and LOS propagation exists for all measurements, the coherence time at all measurement with reference to $s_{\max}$ is approximately constant. Hence, the values of $T_s/T_c$ at $A_2$, $A_3$, $A_4$, $A_5$, and $A_6$ are infinity as long as constant velocity is maintained and LOS propagation exists. In this particular case, the achievable i.i.d given by $\aleph$ is large enough to validate the assumption of ergodic capacity. Also, large time diversity and joint time-frequency diversity gains are obtainable.

### 8.2. Illustrative UWB channel simulation

Let us consider a typical UWB highway infostation propagation channel as shown in Figure 9. The UWB operating frequency band is 3.1-3.6 GHz and the signaling waveform is the Mexican hat wavelet mathematically expressed by $e_I(t) = (1 - t^2)e^{-t^2}$. We assume that the power $P_T$ and duration $T_{\text{pluse}}$ of this function is about 100 mW and 10 ns, respectively.

The geometrical-based single bounce elliptical model [45] is employed in the simulation of this channel. The values of the major axis half-length $a_{\max}$ and minor axis half-length $b_{\max}$ are 33 and 12 m, respectively. The number of potential scatterers is about 5000 and their

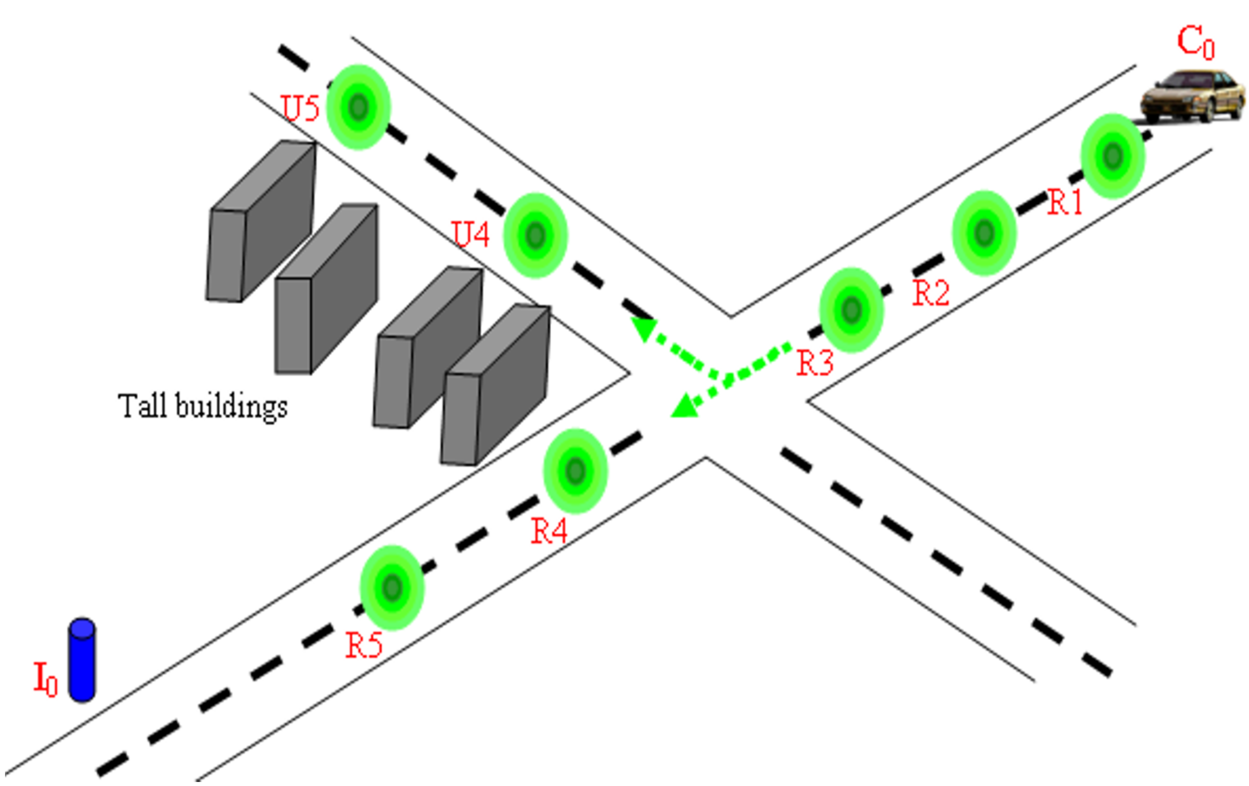


**Figure 9** Simulated LSSUS propagation channel.

positions are assumed fixed over the duration of the simulations. The initial distance $D_0$ between the infostation $I_0$ and the car $C_0$ is 25 m, and the initial speed of the car is 10 m/s. The gains of the infostation and car antennas are taken to be unity. Let us assume that the car is moving from $R_1$ through points $R_2$, $R_3$, $R_4$, and $R_5$ (scenario A) and from $R_1$ through points $R_2$, $R_3$, $U_4$, and $U_5$ (scenario B) as shown in Figure 9.

Scenarios A and B are typical cases that involve LOS and non-LOS propagation. The LSSUS concept can directly be related to the physical propagation scenario in Figure 6 and to the various phases of the mobile's movement.

*Scenario A*: The distances of $I_0$ from $R_1$, $R_2$, $R_3$, $R_4$, and $R_5$ are approximately 25, 23, 20, 16, and 12 m, respectively. And the instantaneous velocities at $R_1$, $R_2$, $R_3$, $R_4$, and $R_5$ are 10, 10, 5, 3, and 5 m/s, respectively. The LSSUS scattering functions at points $R_1$ to $R_1$ are shown in Figure 10. The values of $B_c$ and $T_c$ at the reference point $R_1$ (WSSUS) are 11 MHz and 1.67 ms, respectively. The stationarity parameters for points are shown in Table 1. In Figure 10, the change in the scattering function as the mobile move through the points can be clearly observed, and the LOS propagation path is obvious at all points.

Table 1 shows the computed stationarity parameters and effective diversity order for the positions $R_1$, $R_2$, $R_3$, $R_4$, and $R_5$. In this particular case, the validity of the assumption of ergodic capacity is appropriate mostly at $R_1$, $R_2$, and $R_4$. The effective time, frequency, and joint time-frequency diversities obtainable at $R_1$, $R_2$, $R_3$, $R_4$, and $R_5$ are shown in Figure 11.

The diversity gains are obtained for the case of quadrature phase-shift keying (QPSK). The variation of diversity order with respect to the points $R_1$, $R_2$, $R_3$, $R_4$, and $R_5$ suggests that the use of some adaptive method can improve the performance of the wideband system. The values of $U^{(\Im_F)}$ at $R_1$, $R_2$, $R_3$, $R_4$, and $A_5$ are approximately, 0, 1.25, -2, 0.55, and -1.21%, respectively. And using the same argument discussed in Section 8.1, this nonstationarity information can be employed to adjust the values of $k$ in order to optimize the system performance at any time instant. The values of $U^{(\Im_T)}$ with respect to time can also be computed using (26).

*Scenario B*: The distances of $I_0$ from $R_1$, $R_2$, $R_3$, $R_4$, and $R_5$ are approximately 25, 23, 20, 18, and 19 m, respectively. And the instantaneous velocities at $R_1$, $R_2$, $R_3$, $R_4$, and $R_5$ are 10, 10, 5, 3, and 5 m/s. The LSSUS scattering functions at points $R_1$ to $R_1$ are shown in Figure 12. The values of $B_c$ and $T_c$ at the reference point $R_1$ (WSSUS) are 11 MHz and 1.96 ms, respectively. The computed stationarity parameters and effective diversity order for the positions $R_1$, $R_2$, $R_3$, $U_4$, and $U_5$ are shown in Table 2.

As can be inferred from Table 2, the validity of the assumption of ergodic capacity may not be appropriate since the values of $\aleph$ at the different points may not be enough to ensure long-term averaging. The diversity gains obtained for the case of QPSK at the points $R_1$, $R_2$, $R_3$, $R_4$, and $R_5$ are shown in Figure 13. These figures also provide information about the nonstationarity of the channel and can be employed in providing some form of adaptation to diversity processes in order to improve the performance of the system. The values of $U^{(\Im_F)}$ at $R_1$, $R_2$, $R_3$, $U_4$, and $U_5$ are approximately, 0, 1.25, 2, -9.1, and -5.9%, respectively. Hence, bandwidth utilization can be very low in the non-LOS scenario compared to the LOS case.

### 8.3. Illustrative underwater channel simulation

Let us consider the following example for a single carrier underwater communication between a transmitter $Tx$ submerged at a fixed depth of $h$ = 40 m, and a mobile receiver $Rx$ at the same depth as shown in Figure 14. We consider signaling using the Mexican wavelet. The operational bandwidth $B$ is 10 kHz (100 Hz-10.1 kHz). Let us assume that $Rx$ is moving at a constant speed of 5 m/s from a point $A$ through $B$, $C$, $D$, to $E$, where all points are at the same depth $h$. The temperature of the volume is taken to be constant over the simulation period. For a negligible wind speed, we also assume that the water volume is isotropic, and the floor is smooth and nonabsorptive. Hence, the angle of incidence can be assumed to be equal to the angle of reflection.

Let the time of travel from $A$ to $E$ be sampled at the rate of the valid stationary interval $J_{(\nu)} \approx c/2f_{ref}$, where the distance vector $\boldsymbol{X}$ is $[X_A\ X_B\ X_C\ X_D\ X_E]$ = [1 5 10 15 25] × $J_{(\nu)}$. To be on a safe side, we assume $f_{\text{ref}}$ = 11.1 kHz. For the water depth of $H$ = 100 m and the initial $Tx$-$Rx$ distance of 50 m, the time correlation $\rho = J_0(2\pi \upsilon_{\max,\ X}\, \Delta t_{sym})$ at the different points $A$ to $E$ with respect to the $T_c$ obtained at $J_{(\nu)}$ is shown in Figure 15. The term $J_0(\cdot)$is the zero-order Bessel function of the first kind.

The term $\Delta t_{\text{sym}}$ is a vector of length $T_{c,J_{(\nu)}}/T_{sym}$ with a step size of $T_{\text{sym}}$ (symbol duration). The symbols $\upsilon_{\max,\ X}$and $T_{c,J_{(\nu)}}$ represent the maximum frequency spread at a particular point $A$ to $E$ and the coherence time at the interval $J_{(\nu)}$, respectively.

In Figure 15, we can see that the effect of channel variation within the transmission duration denoted by $T_{c,J_\nu}$ can be assumed to be negligible up to the point marked 'Ω'. This implies that the transmission performance of

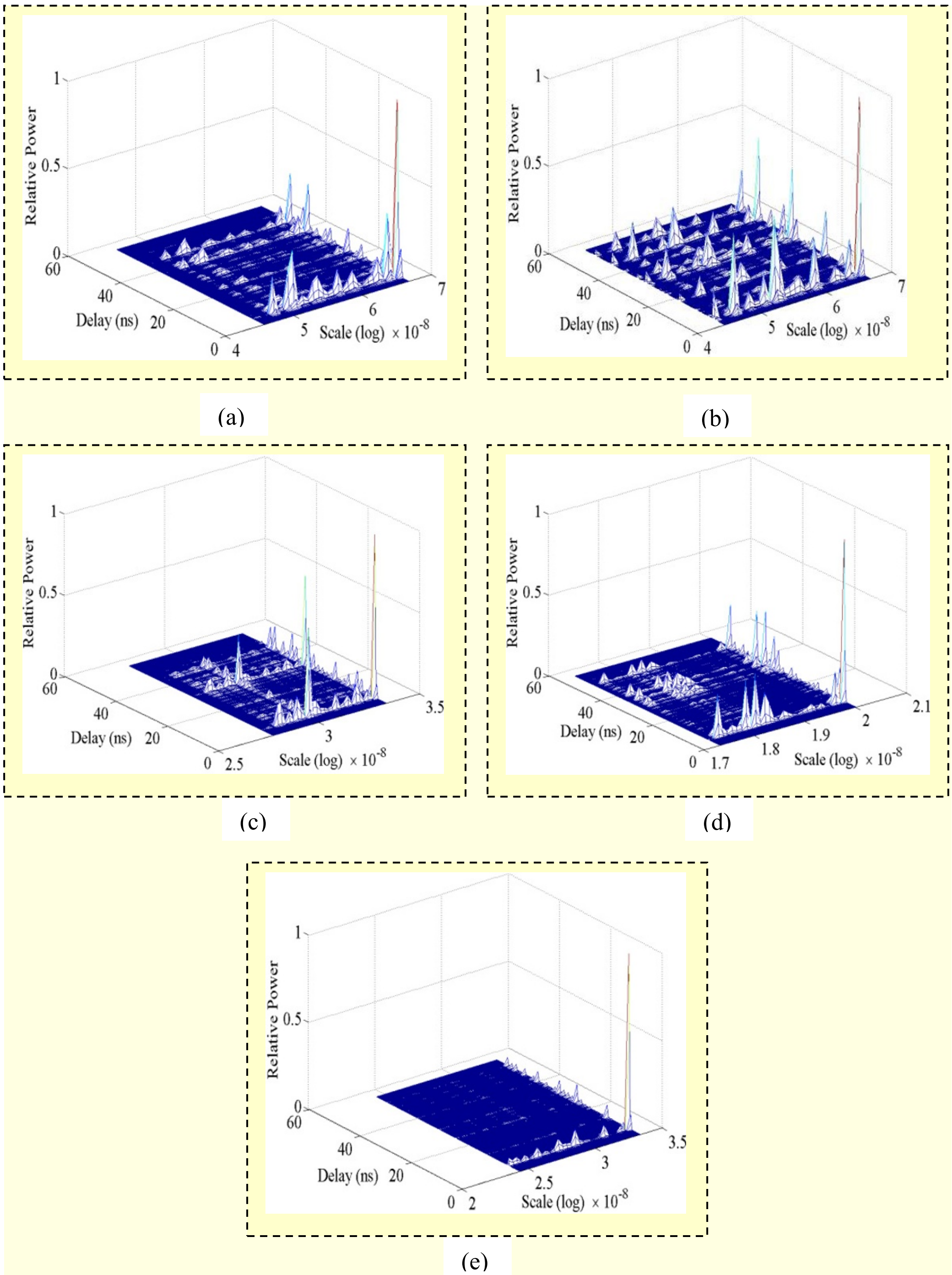


**Figure 10 LSSF: (a) $R_1$, (b) $R_2$, (c) $R_3$, (d) $R_4$, and (e) $R_5$.**

this system using fixed frame size or assuming channel invariance may degrade with time.

To access the available number of effective diversity branches and the validity of assuming an ergodic capacity for this channel, we consider Table 3.

In Table 3, we can see the trend of the variation in the stationarity parameter as $Tx$ moves. The number of available independent fade channels is given by $\aleph$. Thus ergodic capacity can be assumed up to the point for which $\aleph$ is large enough to average out both the

**Table 1 Stationarity parameters and effective diversity order for Scenario A**

| | $R_1$ | $R_2$ | $R_3$ | $R_4$ | $R_5$ |
|---|---|---|---|---|---|
| $B_s$ (GHz) | ∞ | 0.845 | 0.544 | 1.9 | 0.878 |
| $T_s$ (ms) | ∞ | ∞ | 8.33 | 5.95 | 8.33 |
| $\lvert d_{TFD}\rvert = \aleph$ | ∞ | ∞ | 521 | 1302 | 842 |
| $\lvert d_{FD}\rvert$ | ∞ | 81 | 51 | 182 | 84 |
| $\lvert d_{TD}\rvert$ | ∞ | ∞ | 10 | 7 | 10 |

AWGN and the channel fluctuations. When $\aleph$ is not large enough, the outage capacity will be a preferred measure of capacity.

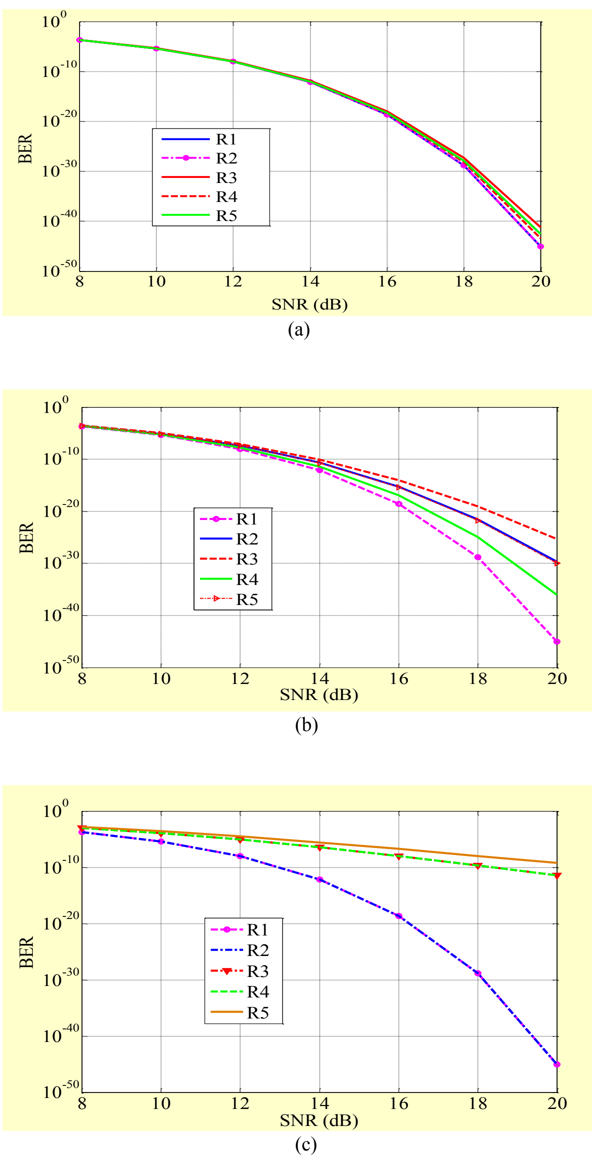


**Figure 11** **BER performance for (a) Joint time-frequency diversity gain, (b) Frequency diversity gain, and (c) time-diversity gain, for Scenario** ***A***.

The parameter $\aleph$ also provides the number of diversity branches for time-frequency diversity (different from delay-Doppler diversity) technique. The values $\aleph_T$ and $\aleph_F$ provide the available number of time and frequency diversity branches, respectively. Let us consider the influence of the assumption of non-WSSUS on time, frequency, Doppler, and delay diversities.

In order to achieve time diversity, a codeword is ideally separated by $T_{c,J_{(\upsilon)}}$. For a frame length $L = T_{c,J_{(\upsilon)}} \times \aleph_T$, it is required that $T_{c,J_{(\upsilon)}}$ should be approximately constant over the segments of $L$. This supposition stems from the WSSUS assumption. In this case we can say that with respect to the $T_{c,J_{(\upsilon)}}$ (without update), the number of diversity branches is fixed. On the other hand, if $T_{c,J_{(\upsilon)}}$ varies across $L$, then correlation among the initially independent fade segments sets in, thus affecting diversity gain. For low SNR which is typical of the covert UWA communications, small variation in diversity order can be meaningful. Hence, when the variation in $T_{c,J_{(\upsilon)}}$ becomes quite significant, update on the $T_{c,J_{(\upsilon)}}$ is required at the transmitter.

We can consider an effective stationarity time $T_{s,\ eff} \leq T_s$ within which $T_{c,J_\upsilon}$ is constant as being one in which the ratio $\aleph_T$ at $A$ to $\aleph_T$ at $A$-$E$ is for instance, $10:\wp$ where $\wp \in \Re^+$ is chosen nontrivially. Hence, when the variation in $T_{c,J_\upsilon}$ becomes quite significant, an update on the $T_{c,J_{(\upsilon)}}$ is required at the transmitter. This may of course increase or decrease the number of the available diversity branches depending on whether the difference between the initial $T_{c,J_{(\upsilon)}}$ and the updated one has a positive or negative value. Of course, when $\aleph_T = 0$, the application of time diversity is of no obvious advantage. This situation occurs when $T_{c,J_{(\upsilon)}} = \infty(\upsilon_{\max} = 0, s = 1)$ or when the channel variation is so rapid that gross nonstationarity of the process has to be considered. In such situation a different diversity technique may be applied. Hence, the LSSUS parameters can be used to track channel variation and ensure that the benefit of time diversity is optimally obtained as shown in Figure 16.

In the case of frequency diversity, a codeword is sent over different frequencies separated by $B_{c,J_{(\upsilon)}}$. The same argument made for the time diversity can also be applied to frequency diversity in which case the effective stationarity bandwidth $B_{s,\ eff} \leq B_s$ defines the frequency segment over which $B_{c,J_\upsilon}$ is constant. Of course the value of $\wp$ in time diversity may not necessarily be the same in the case of frequency diversity.

The LSSUS argument can be extended to the delay (multipath) diversity, Doppler diversity, delay-Doppler

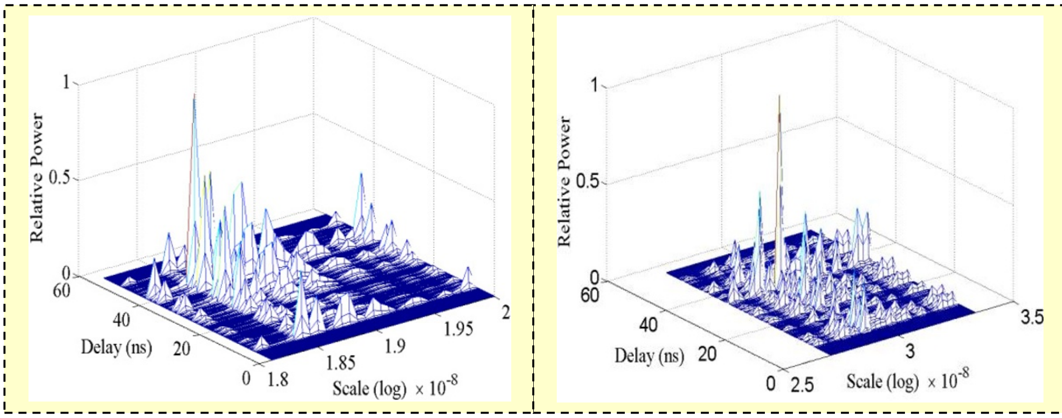


**Figure 12** LSSF: (a) $U_4$ and (b) $U_5$.

diversity, and the delay-scale diversity. To do this, the duality in terms of time/Doppler spread and frequency/delay spread has to be taken into account. The number of delay diversity $N$ and Doppler diversity $Q$ branches are given by $[\tau_{\max} B]$ and $[2\upsilon_{\max} T_{sym}]$, respectively [32]. We note that these expressions of the number of diversity branches are made bearing in mind the assumption of WSSUS. However, it should be noted that both $\tau_{\max}$ and $\upsilon_{\max}$ varies with time. Hence, the variation can appropriately be taken into account using the LSSUS concept where $N(t) = [\tau_{\max}(t)B]$ and $Q(t) = 2\lceil \upsilon_{\max}(t)\, T_{sym} \rceil$. We can also use the same argument above to determine how long $\tau_{\max}$ and $\upsilon_{\max}$ can be considered approximately invariant (WSSUS).

## 9. Conclusion

We presented the time-scale domain characterization of the time-varying wideband propagation channel using the concept of LSSUS which emphasized on the nonstationary properties of the channel. The channel characterization in time-scale domain provides the leverage of carrier frequency-independent computation of channel responses. The statistical assumption termed the LSSUS was also presented and employed in order to evaluate and quantify the degree of nonstationarity of the wideband channel. The LSSUS channel parameters were obtained. By the way of measurement and simulation,

**Table 2 Stationarity Parameters and effective diversity order for Scenario B**

| | $R_1$ | $R_2$ | $R_3$ | $U_4$ | $U_5$ |
|---|---|---|---|---|---|
| $B_s$ (GHz) | ∞ | 0.845 | 0.544 | 0.124 | 0.185 |
| $T_s$ (ms) | ∞ | ∞ | 8.33 | 5.918 | 8.265 |
| $\lvert d_{TFD}\rvert = \aleph$ | ∞ | ∞ | 521 | 84 | 179 |
| $\lvert d_{FD}\rvert$ | ∞ | 81 | 51 | 12 | 18 |
| $\lvert d_{TD}\rvert$ | ∞ | ∞ | 10 | 7 | 9 |

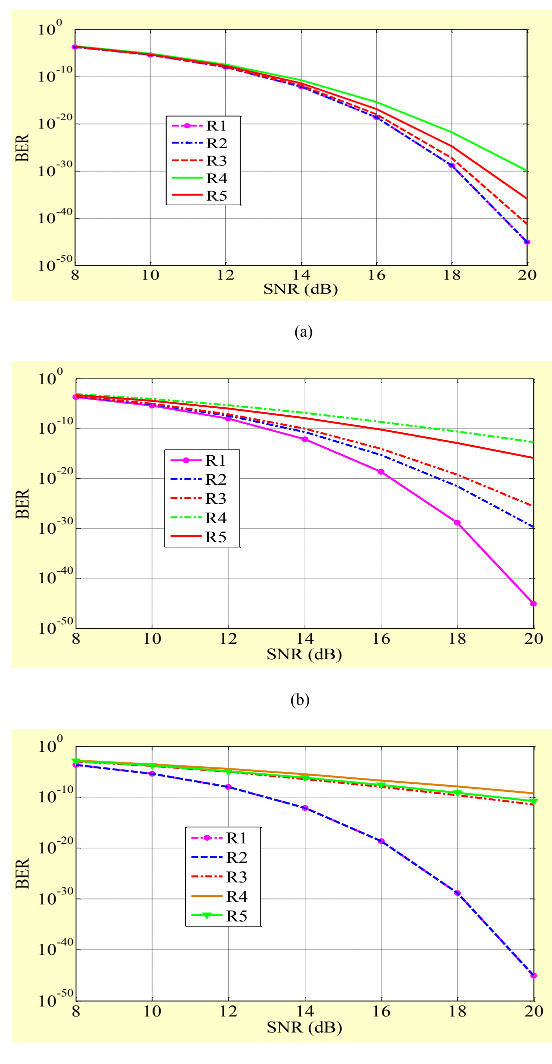


**Figure 13** BER performance for (a) Joint time-frequency diversity gain, (b) Frequency diversity gain, and (c) time-diversity gain, for Scenario *B*.

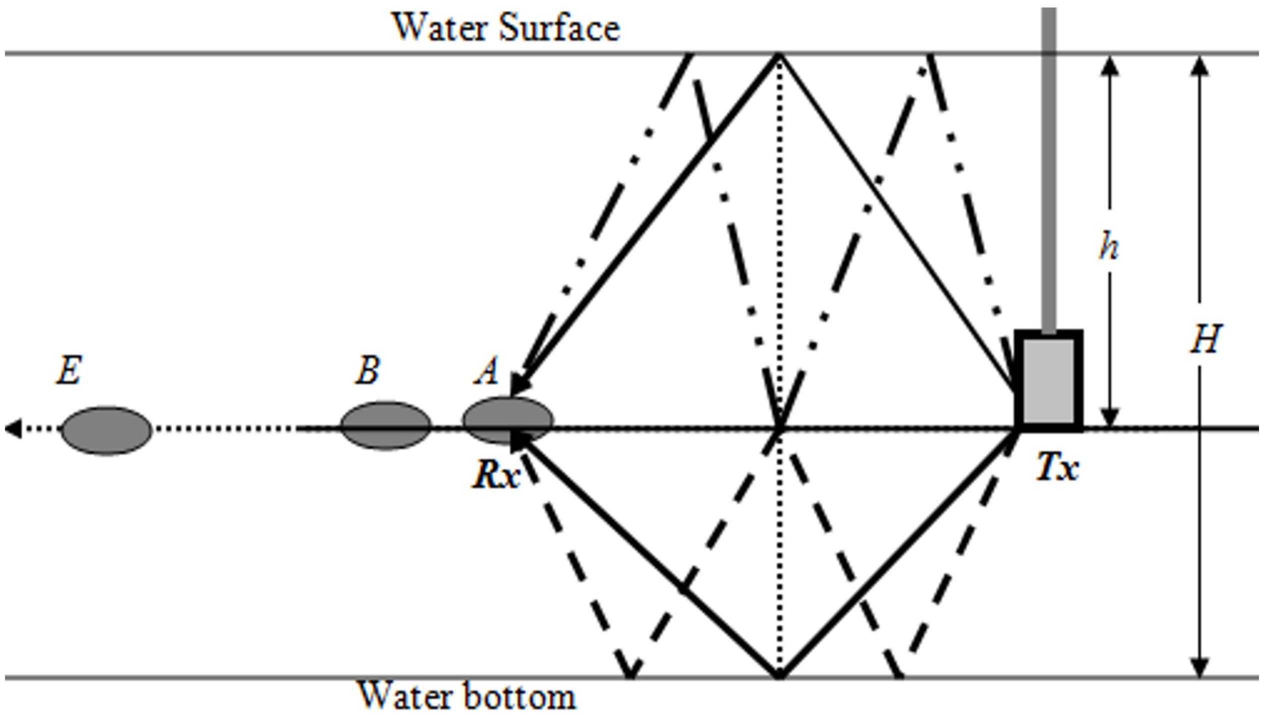


**Figure 14** Illustration of the simplified UWA channel.

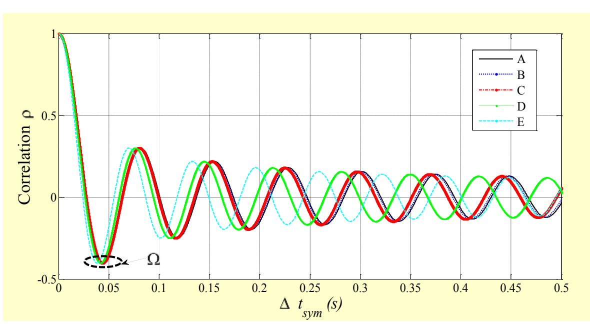


**Figure 15** Time correlation $\rho$ at the different points *A* to *E* with respect to the $T_c$ obtained at $J_{(v)}$.

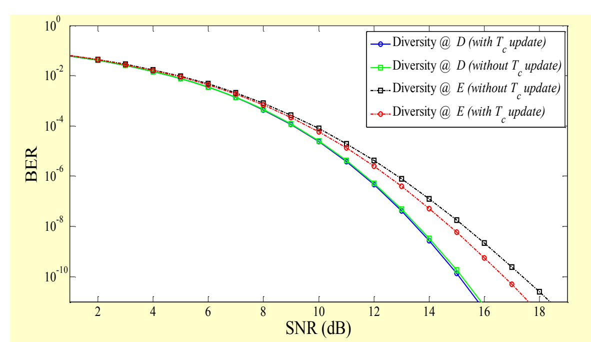


**Figure 16** Performance of time diversity for cases with and without $T_c$ update.

**Table 3 Channel stationarity parameters for the UWA channel**

| *X*. | $B_s$ (kHz) | $T_s$ (ms) | $\|d_{TF}\| = \aleph$ | $\|d_F\|$ | $\|d_T\|$ |
|---|---|---|---|---|---|
| *A* | ∞ | ∞ | ∞ | ∞ | ∞ |
| *B* | 5.254 | 2048 | 107236 | 769 | 139 |
| *C* | 1.791 | 683 | 12193 | 262 | 46 |
| *D* | 0.926 | 342 | 3156 | 135 | 23 |
| *E* | 0.535 | 187 | 996 | 78 | 12 |

these channel parameters were employed in order to analyze the performance of the real and synthesized wideband channels in terms of diversity and channel capacity. Results show that as the assumption of WSSUS becomes violated, the assumption of ergodic capacity and its application becomes unreliable. More also, the gain of the effective diversity varies with the degree of channel stationarity/nonstationarity for different techniques like time, frequency, delay, Doppler and joint delay-Doppler diversities. Hence, it is obvious that the optimal performance of a communication system can be obtained where the instantaneous channel condition is considered. Since the effective diversity gain and channel capacity assumptions depend on the degree of stationarity/nonstationarity, it is therefore necessary to consider some form of adaptive methods for choosing a particular diversity technique or/and channel capacity type. Hence, wideband communication systems that incorporate algorithms based on the LSSUS concept will greatly improve the performance of such systems.

**Acknowledgements**
The authors thank the Ministry of Higher Education (MOHE), Malaysia, for providing financial support for this study through the Grants (4D040 and Q.J130000.7123.02H31) managed by the Research Management Center (RMC), Universiti Teknologi Malaysia (UTM). We also thank the reviewers of this manuscript for their constructive remarks.

**Competing interests**
The authors declare that they have no competing interests.

Received: 18 May 2011 Accepted: 7 December 2011
Published: 7 December 2011

**References**

1. P Bello, Characterization of randomly time-variant linear channel. IEEE Trans Commun. **11**(4), 360–393 (1963). doi:10.1109/TCOM.1963.1088793
2. G Matz, On non-WSSUS wireless fading channels. IEEE Trans Wirel Commun. **4**(5), 2465–2478 (2005)
3. JW Tricia, Wide-sense stationarity of mobile MIMO radio channels. IEEE Trans Veh Technol. **57**(2), 704–714 (2008)
4. LG Weiss, Wavelets and wideband correlation processing. IEEE Sig Process Mag. **11**(1), 13–31 (1994). doi:10.1109/79.252866
5. LG Weiss, Time-varying system characterization for wideband input signals. Els Signal Process. **55**, 295–304 (1996). doi:10.1016/S0165-1684(96)00138-7
6. LH Sibul, MJ Roan, KL Hillsley, Wavelet transform techniques for time varying propagation and scattering characterization, in *Proceeding 32nd Asilomar Conference on Signals, Systems, and Computers*, 1644–1649 (1998)
7. ST Rickard, RV Balan, HV Poor, S Verdu, Canonical time-frequency, time-scale, and frequency-scale representations of the time-varying channels. Int Personal Commun Inf Syst. **5**(2), 197–226 (2005)
8. J Ye, A Papandreou-Suppappola, Discrete time-scale characterization and wideband time-varying systems. IEEE Trans Signal Process. **54**(4), 1364–1375 (2006)
9. AR Margetts, P Schniter, A Swami, Joint scale-lag diversity in wideband mobile direct sequence spread spectrum systems. IEEE Trans Wirel Commun. **6**(12), 4308–4319 (2007)
10. UAK Okonkwo, R Ngah, TA Rahman, Wavelet-domain characterization for mobile broadband communication systems, in *Proceeding IEEE International Conference RFM 2008*, 283–288 (2-3 December 2008)
11. M Pätzold, *Mobile Fading Channels* (John Wiley, England, 2002)
12. AF Molisch, *Wireless Communications*, 2nd edn. (John Wiley, Jersey, 2005)
13. D Tse, P Viswanath, *Fundamentals of Wireless Communications* (Cambridge University Press, New York, 2005)
14. H Dette, P Preuß, M Vetter, A measure of stationarity in locally stationary processes with applications to testing. Discussion Papers Facultät Statistic Technische Universität Dortmund, SFB 823 1–23
15. DJ Goodman, J Borras, NB Mandayam, RD Yates, A new system model for data and messaging services. in *Proceeding IEEE 47th Vehicular Technology Conference*, 969–973 (May 1997)
16. G Rajappan, J Achharya, H Liu, N Mandayam, I Seskar, R Yates, Mobile infostation network technology. in *Proceeding SPIE on Wireless Sensing and Processing*, Orlando, USA (2006)
17. H Chowdhury, JP Mekela, K Pahlavan, Statistical information transfer in random crossing of infostation coverage. in *Proceeding 2005 Finnish Signal Processing Symposium*, Kuopio, Finland (August 2005)
18. A Paier, T Zemen, L Bernado, G Matz, J Karedal, N Czink, C Dumard, F Tufvesson, AF Molisch, CF Mecklenbräuker, Non-WSSUS vehicular channel characterization in highway and urban scenarios at 5.2 GHz using the local scattering function. in *International Workshop on Smart Antennas (WSA 2008)* 26–27 (February 2008)
19. L Bernado, T Zemen, A Paier, G Matz, J Karedal, N Czink, C Dumard, F Tufvesson, M Hagenauer, AF Molisch, CF Mecklenbräuker, Non-WSSUS vehicular channel characterization at 5.2 GHz–spectral divergence and time-variant coherence parameters. in *XXIXth URSI General Assembly* 9–16 (August 2008)
20. A Gehring, M Steinbauer, I Gaspard, M Grigat, Empirical channel stationarity in urban environments, in *Proceeding Europe Perspective Mobile Commun. Conference, EPMCC* (February 2001)
21. G Matz, F Hlawatsh, Time-varying communication channels: fundamentals, resent developments, and open problems, in *Proceeding of 14th EUSIPCO-06, Invited paper* (2006)
22. T Kaiser, F Zheng, *Ultra Wideband Systems with MIMO* (John Wiley, UK, 2010)
23. M Ghavami, LB Michael, R Kohno, *Ultra Wideband Signals and Systems in Communication Engineering* (John Wiley, England, 2007)
24. M Chitre, S Shahabudeen, M Stojanovic, Underwater acoustic communications and networking: Recent advances and future challenges. J Mar Technol Soc. **42**(1), 103–116 (2008). doi:10.4031/002533208786861263
25. AC Singer, JK Nelson, SS Kozat, Signal processing for underwater acoustic communications. IEEE Commun Mag. **47**(1), 90–96 (2009)
26. RA Silverman, Locally stationary random processes. IRE Trans Inf Theory. **3**(3), 182–187 (1957). doi:10.1109/TIT.1957.1057413
27. D Tjøstheim, JB Thomas, Some properties and examples of random processes that are almost wide sense stationary. IEEE Trans Inf Theory **21**(3), 257–262 (1975). doi:10.1109/TIT.1975.1055385
28. E Paparoditis, Validating stationarity assumptions in time series analysis by rolling local periodograms. J Am Stat Assoc. **105**(490), 839–851 (2010). doi:10.1198/jasa.2010.tm08243
29. R Dahlhaus, Local inference for locally stationary time series based on the empirical spectral measure. J Econometrics **151**, 101–112 (2009). doi:10.1016/j.jeconom.2009.03.002
30. E Biglieri, J Proakis, S Shamai, Fading channels: information-theoretic and communication aspects. IEEE Trans Inf Theory **44**(6), 2619–2692 (1998). doi:10.1109/18.720551
31. J Proakis, *Digital Communications*, 5th edn. (McGraw-Hill, New York, 2007)
32. AM Sayeed, B Aazhang, Joint multipath-doppler diversity in mobile wireless communications. IEEE Trans Commun. **47**(1), 123–132 (1999). doi:10.1109/26.747819
33. E Biglieri, *Coding for Wireless Channels* (Springer, New York, 2005)
34. S Bhashyam, AM Sayeed, B Aazhang, Time-selective signaling and reception for communication over multipath fading channels. IEEE Trans Commun. **48**(1), 83–94 (2000). doi:10.1109/26.818876
35. J Ventura-Traveset, G Caire, E Biglieri, G Taricco, Impact of diversity reception on fading channels with coded modulation–part I: coherent detection. IEEE Trans Commun. **45**(6), 563–572 (1997)
36. GW Wornell, Spread-response precoding for communication over fading channels. IEEE Trans Inf Theory **42**(2), 488–501 (1996). doi:10.1109/18.485719
37. AJ Viterbi, *CDMA: Principles of Spread Spectrum Communications* (Addison-Wesley, Boston, 1995)
38. P Pagani, FT Talom, P Pajusco, B Uguen, *Ultra-Wideband Radio Propagation Channels* (John Wiley, 2008)
39. AF Molisch, JF Foerster, M Pendergrass, Channel models for ultrawideband personal area networks. IEEE Wirel Commun. **10**(6), 14–21 (2003). doi:10.1109/MWC.2003.1265848
40. SS Ghassemzadeh, R Jana, CW Rice, W Turin, V Tarokh, Measurement and modeling of an ultra-wide bandwith indoor channel. IEEE Trans Commun. **52**(10), 1786–1796 (2004). doi:10.1109/TCOMM.2003.820755
41. M Di Renzo, F Graziosi, F Santucci, R Minutolo, M Montanari, The ultra-Wide bandwidth outdoor channel: from measurement campaign to statistical modeling. Mob Netw Appl. **11**, 451–467 (2006). doi:10.1007/s11036-006-7193-2
42. SJ Howard, K Pahlavan, Autoregressive modelling of wideband indoor radio propagation. IEEE Trans Commun. **40**(9), 1540–1552 (1992). doi:10.1109/26.163575
43. Y Chen, JA Zhang, D Jayalath, Multiband-OFDM UWB vs IEEE 802.11n: system level design considerations. in *Proceeding VTC 2006-Spring*, Melbourne 1972–1976 (2006)

44. T Pollet, M Blade, M Moeneclaey, BER sensitivity of OFDM systems to carrier frequency offset and wiener phase noise. IEEE Trans Commun. **43**(2-4), 191–193 (1995)
45. RB Ertel, JH Reed, Angle and time of arrival statistics for circular and elliptical scattering models. IEEE J Sel Areas Commun. **17**(11), 1829–1840 (1999). doi:10.1109/49.806814

doi:10.1186/1687-6180-2011-123
**Cite this article as:** Chude-Okonkwo *et al.*: **Time-scale domain characterization of non-WSSUS wideband channels.** *EURASIP Journal on Advances in Signal Processing* 2011 **2011**:123.