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Intermittent Connectivity Wireless Communication Networks

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1. Introduction

Modern computer communication has been developed for providing continuous end-to-end connectivity. There are, however, communications services that are tolerant to both disruptions and transmission delay and, do not require (or cannot be given) continuous connectivity. This chapter focuses on communication over infrastructural wireless communication networks with intermittent connectivity (WCN-IC). Intermittent connectivity is due to either planned or unexpected link disruptions that may results in long delays for the communicating parties. The key assumption for WCN-IC networks is that the coverage is sparse; consequently, as long as the mobile user is in the coverage area of an information node (infocell) the user may download information to the mobile terminal storage for later usage. The communication services that may use such intermittent and high delay connections are characterized by a low degree of interactivity (i.e., broadcasting, messaging, data collection, background file downloading such as a video file, a piece of music, a weather report, etc., and background download of e-mails). In specific, two network paradigms for WCN-IC are studied in this chapter; say the *spatial intermittent connectivity* (SIC) and the *spatial and temporal intermittent connectivity* (STIC) paradigms.
SIC and STIC network models are intended to operate in high traffic-density (sit-through or walk-through) and/or high mobility (drive-through) scenarios such as city centres, business districts, airports, campuses, tourist zones, and highways (Hernández-Valdez & Cruz-Pérez, 2008). Infostations (Ahmed & Miguel-Calvo, 2009; Chowdhury et al., 2010; Chowdhury et al., 2006; Frenkiel et al., 2000; Small & Haas, 2007; Small & Haas, 2003), hotspots (Doufexi et al., 2003; Goodman et al., 1997; Frenkiel & Imielinski, 1996), drive-through internet and wireless local networks-based architectures (Ott & Kutscher, 2005; Ott & Kutscher, a, 2004; Ott & Kutscher, b, 2004; Zhou et al., 2003), roadside infrastructures (Sichitiu & Kihl, 2008; Tan et al., 2009; Wu and Fijumoto, 2009), cell-hoping systems (Hassan & Jha, 2004; Hassan & Jha, 2003; Hassan & Jha, 2001), and relay stations (Pabst et al., 2004; Yanikomeroglu, 2004) are examples of SIC networks, while the Intermitstations system proposed in (Hernández-Valdez et al., a 2003; Hernández-Valdez et al., b 2003) is an example of a STIC network. Even though the naming varies in terms of functionalities they share the main characteristic of WCN-IC networks: the overall spatial coverage of these networks is sparse.

1.1 Capacity-delay trade-off in wireless networks with intermittent connectivity

In general, wireless communication networks are characterized by their capacity-delay trade-off (Small & Haas, 2003). In traditional cellular systems, for instance, within the limitations of wireless radio link reliability, constant connectivity is provided and the worst case signal to noise ratio (SIR) dictates the data rate that can be used. Thus, although both the delay and probability of disruption are small, the capacity is limited as well. Instead, wireless communication networks with spatial intermittent connectivity provide reduced coverage keeping the distance between information nodes (base stations or access points) unchanged (Hernández-Valdez & Cruz-Pérez, 2008). This allows the worst case SIR to be improved and, as a consequence, higher data rates provisioning (Iacono & Rose, 2000). However, due to both, the lack of continuous spatial coverage and users' mobility, these high data rates comes at the expense of providing spatial intermittent connectivity only. In mobile ad hoc networks, the transmission range is significantly smaller than in cellular networks and, as a result, the reuse of radio channels can significantly improve the overall network capacity. Nevertheless, continuous temporal connectivity cannot be guaranteed; nodes can separate from the network leading to network partition.

Clearly, the choice of technology depends on the traffic types that the network is intended to support. In IMT-2000, supported traffic types are divided into four different quality of service (QoS) classes (Recommendation, 2000). These traffic classes are: conversational, streaming, interactive, and background. The main distinguishing factor among these traffic classes is their ability to tolerate delay. Under this framework, a cellular system could be more suitable to support conversational and streaming applications such as real-time constant bit rate voice traffic, videoconferencing, etc. On the other hand, SIC networks could be used mainly for applications that can tolerate significant delay; that is, SIC networks can easily and efficiently support background applications. The main difference between interactive and background classes is that the former is mainly used by interactive applications (i.e., gaming, interactive e-commerce, interactive Web browsing, database read types of traffic, telemetry traffic, etc.); while the later is meant for best effort services (i.e., background download of e-mails or background file downloading) (Recommendation, 2000).

On the other hand, STIC networks have been conceived to improve system performance in terms of both delay and delivery probability (disruption connectivity) relative to SIC networks. The STIC paradigm consists of one or more spatially non-overlapping and coordinated sets of information nodes operating in a temporal intermittent and sequential fashion. This temporal sequential operation mode allows STIC systems to spatially distribute the total system capacity. STIC networks can easily and efficiently support background, interactive, and in some special cases, conversational applications.

To clearly and directly quantify performance improvement of STIC over SIC wireless communication networks, a simple but illustrative one-dimensional (drive-through) scenario is considered. Then, general mathematical expressions for the probability distribution function (pdf) of the connectivity delay[1] in terms of the information node radius, distance between adjacent coverage zones, *temporal reuse factor*, *temporal intermittence factor*, minimum necessary time to establish connectivity, and parameters of the user's

[1] Connectivity delay is the time elapsed from the session attempt to the moment at which the mobile node first come within transmission range of an information node.

velocity probability distribution function, are derived and numerically evaluated. The connectivity delay improvement in STIC networks is achieved at the expense of a slight system capacity (per area unit) loss. Nevertheless, as discussed in Section 4.4, this capacity loss of STIC relative to SIC networks could be negligible and/or acceptable because of the spatial random nature of information generation/request by mobile terminals and the greater disruption periods in SIC networks; and, more importantly, the broader gamma of traffic classes that could be supported in STIC networks.

2. Wireless communication networks with spatial intermittent connectivity

Cellular systems are deployed to provide anywhere/anytime services. This is translated into ubiquitous connectivity requirements, which in turn requires significant and expensive infrastructure. To keep good quality of service, ubiquitous connectivity requires that transmitted power should be increased as the distance from the information node (base station/access point) increases. While this is an appropriate design for conversational, and in general, real-time services, it has been shown that this is not the case for data services (Yates & Mandayam, 2000; Yuen et al., 2003, Iacono & Rose, a 2000; Iacono & Rose, a 2000). It is well known that the optimal use of a set of channels is achieved by water-falling solutions, in which more power is transmitted on the better channels (Yates & Mandayam, 2000). These arguments imply that more power should be transmitted the closer the mobile node is to the information node. This was the driving force in developing the here generically referred to as wireless communication networks with *spatial intermittent connectivity* (SIC). An example of a SIC architecture is the Infostations system which was originally proposed at Wireless Information Networks Laboratory (WINLAB) (Frenkiel & Imielinski, 1996) and has been classified as a promising 4th generation (4G) wireless data system concept. The issue of cost-per-bit was the driving force that motivated the development of the Infostations model at WINLAB (Frenkiel, 2002). Researchers at WINLAB realized that "free bits" are as a matter of course provided by the Internet. Additionally, Infostations systems and, in general, WCN-IC networks are intended, but not limited, to use unlicensed bands. In these bands, the cost of wireless data transfers need not be greater than that of wire-line LAN technology and, as a consequence, SIC wireless communication networks are expected to provide the free bits that wireless data services require (Frenkiel et al., 2000).

In SIC networks, small and separated zones of high bit rate connectivity provide low cost and low power access to information services in a mobile environment. The use of small disjoint geographical connectivity areas in SIC networks is translated into a significant increase in cell (or per information node) capacity compared to cellular systems. The reason is twofold: reduced coverage allows smaller frequency reuse cluster size and higher-level modulations and/or more spectrally efficient channel coding schemes. The first effect leaves more bandwidth available per information node, whereas the second improves the efficiency per unit of bandwidth (Yates & Mandayam, 2000). As a result, the vast array of contiguous cells which is needed in conversational systems to provide continuous connectivity (ubiquitous coverage) is reduced to a relatively small number, with a considerable reduction in infrastructure.

Furthermore, efficient utilization of the limited battery power of the mobile nodes is an added incentive to employ SIC networks. Nevertheless, because of users' mobility, the high data rates in SIC networks come at the expense of providing spatial intermittent connectivity only. At this point, it is important to mention that SIC networks can be also defined as manywhere/anytime architectures because they provide, from the spatial point of view, intermittent connectivity (*manywhere*) and within the coverage of an information node connection can be provided in a continuous fashion (*anytime*). On the other hand, cellular networks are defined as anywhere/anytime architectures because they provide, from the spatial point of view, continuous connectivity (*anywhere*) and, within the coverage of a base station, the connectivity can be provided in a continuous fashion (*anytime*). To avoid confusion, it is important to remark that the anywhere, manywhere, anytime, and manytime adjectives used in this chapter are given from the network (not the user) point of view.

On the other hand, the main drawbacks of SIC networks are the significant connectivity delays and service disruption that mobile nodes may experience. Thus, SIC networks are mainly suitable and efficient for applications that need to transfer huge information data files and tolerate significant delays. Fig. 1.a illustrates the SIC paradigm and compares it against the cellular model (Fig. 1.b). In Fig. 1 both infocells coverage area and cells coverage area are represented by continues-line hexagons.

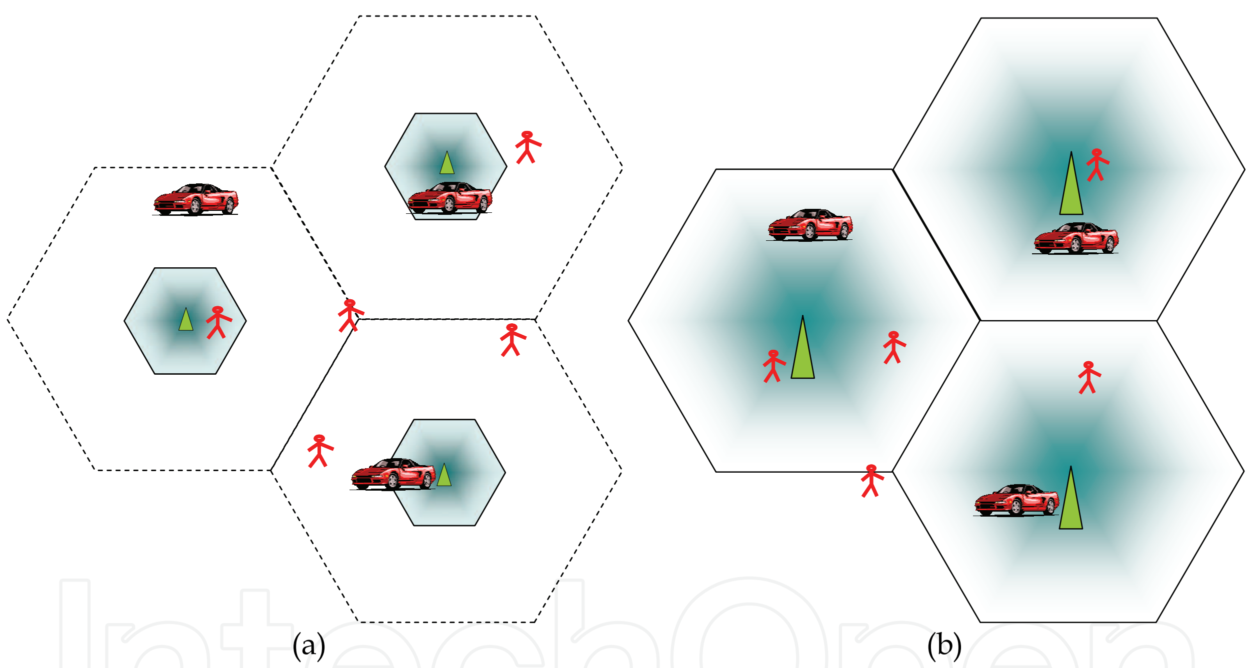

Fig. 1. Wireless communication networks: (a) SIC and (b) Cellular paradigms

SIC networks are definitively not suitable for delay sensitive applications and, as stated before, their main drawbacks are connectivity delay and probability of disruption that mobile nodes can suffer. Moreover, no matter how creative and successful the placement of the information nodes is, there remains the possibility that a particular user will not access an information node within an acceptable time period. In order to overcome this problem, the authors of (Yuen et al., 2003) extended the Infostation concept by allowing mobile nodes to act as mobile Infostations and exchange files to other nodes in their proximity. In this way, the delay and the probability of delivery can be significantly reduced. However, spreading the information to other nodes consumes network capacity and entails routing problems. Thus, again, a capacity-delay trade-off has to be faced. To overcome these drawbacks, wireless communication networks with *spatial and temporal intermittent* *connectivity* (STIC networks) were proposed in the literature (Hernández-Valdez & Cruz-Pérez, 2008). STIC networks are studied in the next section.

3. Wireless communication networks with spatial and temporal intermittent connectivity

In this section, the *spatial and temporal intermittent connectivity* (STIC) network paradigm is explained. The STIC paradigm consists of one or more spatially non-overlapping but coordinated sets of information nodes (i.e., access points) operating in an intermittent and sequential fashion. Each set of information nodes works periodically during a fixed time period. In other words, the transceivers of each set of information nodes are sequentially switched from *active* to *sleep* cycles[2]. The time interval a set of information nodes is in the *active* cycle is denoted as t_{on}, and the time interval a set of information nodes is in the *sleep* cycle is denoted as t_{off}. This temporally-intermittent and sequentially-coordinated operation mode allows STIC networks (relative to SIC networks) to spatially distribute the total system capacity. In this way, STIC networks can significantly reduce both connectivity delay and probability of disruption relative to SIC networks at expense of increased system complexity[3] and slight reduction of capacity per information node. Clearly, this capacity loss is due to both the spatial distribution of mobile nodes and the spatial distribution of the total system capacity by temporal intermittent connectivity (Section 4.4 of this chapter presents a comprehensive discussion on system capacity loss of STIC networks relative to SIC networks). Additionally, this capacity loss is a function of both the spatial reuse factor and the *temporal reuse factor* (defined as the inverse of the fraction of time a given set of information nodes is in the *active* cycle). For instance, Fig. 2. illustrates the architecture of a hexagonal shaped STIC network composed of two different sets of information nodes (one of them represented by the light grey infocells and the other by the diffusive blue ones). These two different sets of information nodes operate in a coordinated sequential form, that is, while the light grey information nodes are in the *active* cycle, the diffusive blue ones are in the *sleep* cycle, and vice versa. Notice that t_{on}, t_{off}, *temporal reuse factor*, *temporal intermittence factor* (defined as the ratio between t_{on} and t_{off}), cell size of information nodes, and distance between adjacent coverage zones, for each set of information nodes in STIC networks are design parameters and could be chosen according to the nature of traffic classes (i.e., required QoS in terms of delay), spatial distribution of mobile nodes, interference conditions, etc.

To clearly appreciate the real difference between SIC and STIC networks the following example is given. Let us consider the SIC and STIC networks represented, respectively, by figure 1.a and figure 2. Suppose that cell sizes of STIC and SIC networks are equals, that is the radius of infocells shown in Fig 1.a and 2 are equal. Suppose, also, that propagation characteristics and interference conditions are similar in both systems. Then, in the SIC

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[2] Observe that this sequential and intermittent operation mode can be implemented at the data-link layer using well-developed and efficient MAC protocols. Choosing the more suitable MAC protocol or proposing new ones for STIC networks is out of the scope of this work and, it is left as material of future research.

[3] Contrary to SIC networks, a large number of information nodes and synchronization between sets of information nodes are required in STIC networks. Moreover, in STIC networks some kind of handover technique could be required (in order to provide, for example, real time services).

network, the total system capacity (say C_T) is provided only within the coverage area of each information node. On the other hand, in the STIC network, C_T is shared (in a sequential and temporally intermittent fashion) by each pair of two information nodes (referring to Fig. 2, one of them from the light grey set of information nodes and the other from the diffusive blue one). Here, it is important to mention that in SIC networks it is assumed that high-speed information islands may be provided by different administrations (Yates & Mandayam, 2000; Yuen et al., 2003, Iacono & Rose, a 2000; Iacono & Rose, a 2000). Also, of importance, it is assumed that no synchronization between information nodes is required in SIC networks. On the other hand, in STIC networks, coordinated sets of high-speed information nodes could be provided by a larger telecommunication provider or by different small administrations working cooperatively. In any case, synchronization between sets of information nodes in STIC networks is required. This synchronization task could be based, for example, on the global position system (GPS).

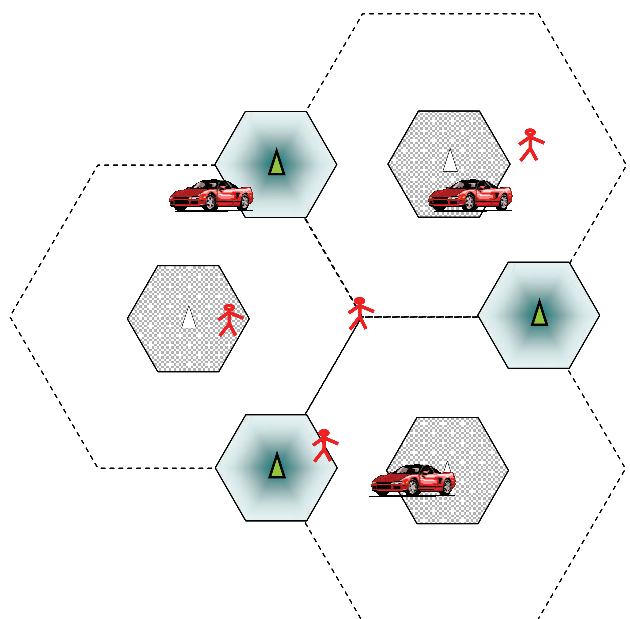

Fig. 2. Wireless communication network with spatial and temporal intermittent connectivity

3.1 Configuration modes in STIC networks

Now let us move to the STIC network configuration. In general, STIC networks have two possible configurations. One of them is the so called *manywhere/manytime* (STIC-M/M) approach and the other one is the so called *anywhere/manytime* (STIC-A/M) approach. For an easy explanation, let us consider the one-dimensional scenarios shown in Fig. 3. Fig. 3 compares the cellular, SIC and STIC paradigms. In Fig. 3.a, r_c represents cell size for the cellular network; in Fig. 1.b, r_s and l represent, respectively, the coverage size of information nodes and distance between adjacent information nodes for the SIC network; in Fig. 1.c, r_m and l_m represent, respectively, the coverage size of information nodes and distance between adjacent information nodes for a STIC-M/M network.The STIC-M/M and STIC-A/M approaches are represented, respectively, by Figs. 3.c and 3.d. The former provides, from the spatial point of view, intermittent connectivity (*manywhere*) and within the coverage of an information node the *information service* (connection) is provided in a sequential and temporally intermittent fashion (*manytime*). The later provides, from the spatial point of view of view, continuous connectivity (*anywhere*) and within the coverage of an information node the *information service* (connection) is provided in a sequential and temporally intermittent fashion (*manytime*).

The STIC-M/M network paradigm is characterized by discontinuous coverage service but with lower connectivity delay and probability of service disruption relative to the SIC network paradigm. On the other hand, the STIC-A/M paradigm, similar to cellular networks, provides continuous connectivity but in a temporal intermittent and sequential fashion. It is important to note that, for practical purposes, some degree of overlapping between adjacent information nodes of STIC-A/M networks will be necessary to support handover. In fact, assuming there exist IP address change at each information node (all IP networks), a smooth handover technique could be implemented. Also, of importance is to note that, with an appropriated design, the STIC-A/M network model opens the possibility to support more delay sensitive applications services than those supported by SIC networks. Thus, the STIC network paradigm gives network designers more control and flexibility over both the degree of delay and disruption tolerance that WCN-IC systems can achieve. Due to this flexibility, STIC networks are intended to provide wireless communication services in a variety of different environments, including highways, hot spots in urban zones, airports, etc. The type of configuration used depends on market and operator needs. STIC networks could be used to cover hotspot areas where intensive high data rate transfers are requested, such as tourist and business zones. We would like to emphasize, however, that STIC and cellular networks are meant to be complementary rather than competitive technologies that altogether provide a complete set of mobile communication services. Also, SIC networks such as WLAN-based architectures, Infostations, and Ad-hoc Networks (Grossglauser & Tse, 2001; Perkins, 2001; Wu & Fujimoto, 2009) will play an important role to this end.

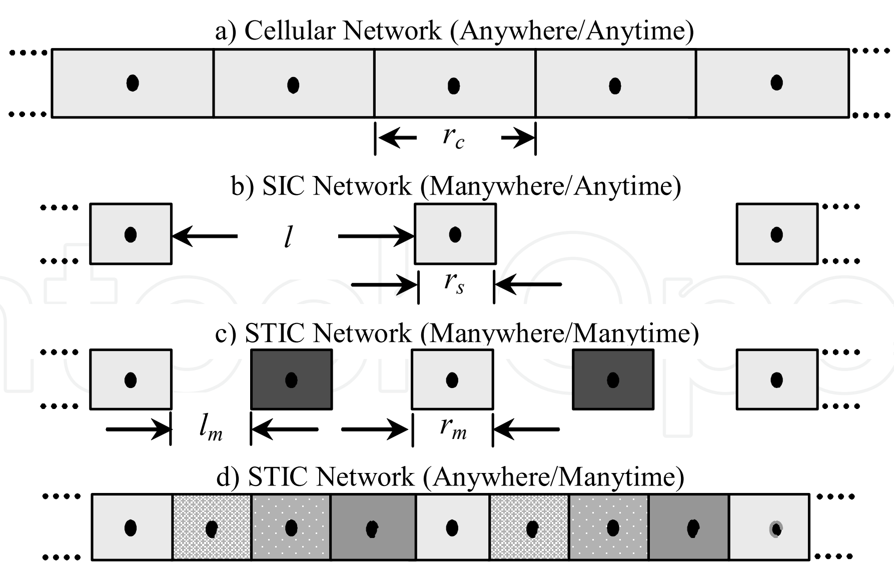

Fig. 3. Cellular, SIC, and STIC one-dimensional network scenarios

4. Connectivity delay analysis

In this section, the time elapsed from the session attempt to the moment at which the mobile node first come within transmission range of an information node in both SIC and STIC one-dimensional networks is mathematically analysed using the system model presented in Section 4.1. We refer to this time as the connectivity delay. The analysed one-dimensional SIC and STIC models (represented, respectively, by an Infostations and Intermitstations systems) are shown in Fig. 3.b and 3.d, respectively. Sub-sections 4.2 and 4.3 are devoted to the connectivity delay analysis for SIC and STIC networks, respectively. In both cases, the following methodology is used to study the connectivity delay. First, using the total probability theorem and transformations of random variables, general mathematical expressions for the cumulative distribution function (cdf), probability density function (pdf), and the moment generating function (mgf) of the connectivity delay are derived. Then, using the mgf, mathematical expressions for the mean and standard deviation of the connectivity delay are obtained. In the analysis, the minimum necessary time to establish connectivity, say Δt, is taken into account. Finally, in sub-section 4.4 a comprehensive discussion on the system capacity loss of STIC networks relative to SIC networks is offered.

4.1 System model

A one-dimensional drive-through scenario is considered where the SIC system is composed of discontinuous cells (small coverage areas or information islands) of length r_s and equally spaced by a distance l, see Fig. 3.b. On the other hand, the STIC model is composed of one (or more) non-overlapping but coordinated sets of information nodes operating sequentially, see Figs. 3.c and 3.d. Free-flowing highway traffic is considered where the velocity, **V**, of mobile nodes is assumed to be a random variable (RV) with arbitrary probability distribution with maximum speed d, and minimum speed c, and it is assumed to remain constant at least from the duration of the session (El-Dolil et al., 1989). For numerical evaluations, two particular cases for the pdf of **V** were considered: truncated normal (TN) and uniform (UN). The pdf of **V** is given by

$$f_{\mathrm{V}}(v)=\begin{cases} k\dfrac{1}{\sqrt{2\pi}\sigma}e^{-\frac{(v-\mu)^2}{2\sigma^2}} & ;\text{for } c<v\le d \\ 0 & ;\text{otherwise} \end{cases} \tag{1}$$

if **V** is truncated normally distributed, or by

$$f_{\mathrm{V}}(v)=\begin{cases} \dfrac{1}{(d-c)} & ;\text{for } c<v\le d \\ 0 & ;\text{otherwise} \end{cases} \tag{2}$$

if **V** is uniformly distributed. Where $k = \Phi[(d+\mu)/\sigma] - \Phi[(d-\mu)/\sigma]$, μ and σ are, respectively, the mean and standard deviation of a Gaussian random variable and

$$\Phi(x)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x} e^{-\frac{\xi^2}{2}}d\xi \,. \tag{3}$$

It can be readily shown that μ and σ are related with the mean (μ_t) and variance (σ_t^2) of the truncated normal random variable **V** as follows

$$\mu_t = \mu + \frac{k\sigma}{\sqrt{2\pi}}\left(e^{-\frac{(c-\mu)^2}{2\sigma^2}} - e^{-\frac{(d-\mu)^2}{2\sigma^2}}\right) \tag{4a}$$

$$\sigma_t^2 = \sigma^2 + \frac{k\sigma}{\sqrt{2\pi}}\left[\left(c-\mu+\frac{k\sigma}{\sqrt{2\pi}}\right)e^{-\frac{(c-\mu)^2}{2\sigma^2}} - \left(d-\mu+\frac{k\sigma}{\sqrt{2\pi}}\right)e^{-\frac{(d-\mu)^2}{2\sigma^2}}\right] \tag{4b}$$

4.2 Connectivity delay analysis in the SIC network

In this section analytical expressions for the pdf, cdf, and mgf of the connectivity delay in a one-dimensional SIC network are obtained. Let the random variable (RV) $\mathbf{T}_i$ be the connectivity delay and let us define the random variables (RVs) $\mathbf{X}_1$ and $\mathbf{X}_2$ as follows. Assume that the session is originated outside (inside) the *information node coverage area* (infocell), the random variable $\mathbf{X}_1$ ($\mathbf{X}_2$) represents the distance; from the session attempt, between the *mobile node* (MN) and the nearest *information node* (IN) boundary in the direction of user's movement, see Fig. 4. It is reasonable to assume that the RVs $\mathbf{X}_1$ and $\mathbf{X}_2$ are uniform in the intervals (0, l) and (0, r_s) , respectively. Then, given the following events:

A={The session attempt occurs when the MN is outside the infocell},

A^c={The session attempt occurs when the MN is inside the infocell},

B={The MN successfully access the system via the current IN | A^c},

B^c={The MN does not access the system via the current IN | A^c}, the cdf of $\mathbf{T}_i$ can be expressed as:

$$F_{\mathbf{T}_i}(\tau) = P(\mathbf{T}_i \le \tau) = P(\mathbf{T}_i \le \tau \,|\, A)P(A) + P(\mathbf{T}_i \le \tau \,|\, A^c)P(A^c) \tag{5}$$

where

$$P(A) = P_{out} = \frac{l}{r_s + l},$$

$$P(A^c) = P_{in} = \frac{r_s}{r_s + l},$$

$$P(\mathbf{T}_i \le \tau \,|\, A) = P\left(\frac{\mathbf{X}_1}{\mathbf{V}} \le \tau\right),$$

$$\begin{aligned} P(\mathbf{T}_i \le \tau \,|\, A^c) &= P(\mathbf{T}_i \le \tau \mid B)P(B) + P(\mathbf{T}_i \le \tau \mid B^c)P(B^c) \\ &= P\left(\frac{\mathbf{X}_2}{\mathbf{V}} > \Delta t\right)u(\tau) + P\left(\frac{\mathbf{X}_2 + l}{\mathbf{V}} \le \tau \,\middle|\, \frac{\mathbf{X}_2}{\mathbf{V}} \le \Delta t\right)P\left(\frac{\mathbf{X}_2}{\mathbf{V}} \le \Delta t\right) \\ &= P\left(\frac{\mathbf{X}_2}{\mathbf{V}} > \Delta t\right)u(\tau) + P\left(\frac{\mathbf{X}_2}{\mathbf{V}} \le \Delta t, \frac{\mathbf{X}_2 + l}{\mathbf{V}} \le \tau\right), \end{aligned}$$

where u(τ) is the unit step function. The first (second) term on the right hand of (5) does represent the case when the session attempt is originated outside (inside) the infocell.

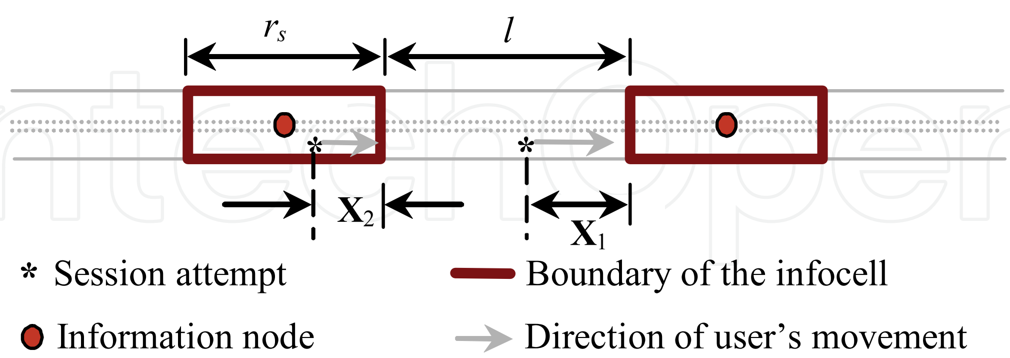

Fig. 4. One-dimensional SIC scenario

Given the following transformations: $\mathbf{Z}_1=\mathbf{X}_1/\mathbf{V}$, $\mathbf{Z}_2=\mathbf{X}_2/\mathbf{V}$, $\mathbf{Z}_3=(\mathbf{X}_2+l)/\mathbf{V}$, it is necessary to find the cdf of $\mathbf{Z}_1$, $\mathbf{Z}_2$, and the joint cdf of $\mathbf{Z}_2$ and $\mathbf{Z}_3$. To this end, let us define the RV $\mathbf{Z}$ as follows: $\mathbf{Z}=\mathbf{X}/\mathbf{V}$, where $\mathbf{X}$ is a uniform RV in the interval (a, b), and $\mathbf{V}$ is a RV with general probability distribution whose possible outcomes are limited in the interval (c, d). Assuming that $\mathbf{X}$ and $\mathbf{V}$ are statistically independent, the cdf of $\mathbf{Z}$ can be written as follows

$$F_Z(z)=\begin{cases} 0 & ;\text{ for } z<a/d \\ G_1(z)=\int_{a/z}^{d}\int_{a}^{zv} f_V(v)f_X(x)\,dxdv & ;\text{ for } a/d\le z\le a/c \\ G_2(z)=\int_{c}^{d}\int_{a}^{zv} f_V(v)f_X(x)\,dxdv & ;\text{ for } a/c<z\le b/d \\ G_3(z)=1-\int_{c}^{b/z}\int_{zv}^{b} f_V(v)f_X(x)\,dxdv & ;\text{ for } b/d<z\le b/c \\ 1 & ;\text{ for } z>b/c \end{cases} \tag{6a}$$

if $a/c\le b/d$, and as

$$F_Z(z)=\begin{cases} 0 & ;\text{ for } z<a/d \\ G_1(z)=\int_{a/z}^{d}\int_{a}^{zv} f_V(v)f_X(x)\,dxdv & ;\text{ for } a/d\le z\le b/d \\ G_4(z)=\int_{a}^{b}\int_{x/z}^{d} f_V(v)f_X(x)\,dvdx & ;\text{ for } b/d<z\le a/c \\ G_3(z)=1-\int_{c}^{b/z}\int_{zv}^{b} f_V(v)f_X(x)\,dxdv & ;\text{ for } a/c<z\le b/c \\ 1 & ;\text{ for } z>b/c. \end{cases} \tag{6b}$$

if $a/c>b/d$, where $f_X(x)$ is the pdf of $\mathbf{X}$.

For $\Delta t < r_s/d$, and Δt given as a parameter, the joint cdf of $\mathbf{Z}_2$ and $\mathbf{Z}_3$ is given by

$$F_{Z_2,Z_3}(\tau)=\begin{cases} 0 & ;\text{ for } \tau < l/d \\ G_5(\tau)=\int_0^{d\tau-l}\int_{\frac{x+l}{\tau}}^{d} f_V(v) f_X(x)\,dvdx & ;\text{ for } l/d \le \tau \le \Delta t + l/d \\ G_6(\tau)=\int_{l/\tau}^{\frac{l}{\tau-\Delta t}}\int_0^{\tau v-l} f_V(v) f_X(x)\,dxdv + \\ \qquad + \int_{\frac{l}{\tau-\Delta t}}^{d}\int_0^{\Delta t v} f_V(v) f_X(x)\,dxdv & ;\text{ for } \Delta t + l/d < \tau \le l/c \\ G_7(\tau)=\int_c^{\frac{l}{\tau-\Delta t}}\int_0^{\tau v-l} f_V(v) f_X(x)\,dxdv + \\ \qquad + \int_{\frac{l}{\tau-\Delta t}}^{d}\int_0^{\Delta t v} f_V(v) f_X(x)\,dxdv & ;\text{ for } l/c \le \tau \le \Delta t + l/c \\ G_8(\tau)=\int_c^{d}\int_0^{\Delta t v} f_V(v) f_X(x)\,dxdv & ;\text{ for } \Delta t + l/d < \tau \le \infty \end{cases} \tag{7a}$$

if $\Delta t \le l/c - l/d$, and as

$$F_{Z_2,Z_3}(\tau)=\begin{cases} 0 & ;\text{ for } \tau < l/d \\ G_5(\tau)=\int_0^{d\tau-l}\int_{\frac{x+l}{\tau}}^{d} f_V(v) f_X(x)\,dvdx & ;\text{ for } l/d \le \tau \le l/c \\ G_9(\tau)=\int_c^{d}\int_0^{\tau v-l} f_V(v) f_X(x)\,dxdv & ;\text{ for } l/c < \tau \le \Delta t + l/d \\ G_7(\tau)=\int_c^{\frac{l}{\tau-\Delta t}}\int_0^{\tau v-l} f_V(v) f_X(x)\,dxdv + \\ \qquad + \int_{\frac{l}{\tau-\Delta t}}^{d}\int_0^{\Delta t v} f_V(v) f_X(x)\,dxdv & ;\text{ for } l/d \le \tau - \Delta t \le l/c \\ G_8(\tau)=\int_c^{d}\int_0^{\Delta t v} f_V(v) f_X(x)\,dxdv & ;\text{ for } \Delta t + l/c < \tau \le \infty \end{cases} \tag{7b}$$

if $\Delta t > l/c - l/d$, where $f_X(x)$ is the pdf of **X** with a=0, and b=r_s.
Using (6) it is straightforward to obtain the cdf, pdf, and mgf, of the RVs $\mathbf{Z}_1$ and $\mathbf{Z}_2$. This task is left to the reader as an exercise. In the following analysis, $F_{z_n}(\tau)$, $f_{z_n}(\tau)$, and $\varphi_{Z_n}(\tau)$, represent, respectively, the cdf, pdf, and mgf, of the RV $\mathbf{Z}_n$ (n = 1, 2). In this way, the cdf of the connectivity delay for the SIC network can be written as

$$F_{T_i}(\tau)=P_{out}F_{Z_1}(\tau)+P_{in}F_{Z_2,Z_3}(\tau)+P_{in}\left\langle 1-F_{Z_2}(\Delta t)\right\rangle u(\tau). \tag{8}$$

Thus, the pdf of $\mathbf{T}_i$ is found by differentiating (8). Thus

$$f_{T_i}(w)=P_{out}f_{Z_1}(\tau)+P_{in}f_{Z_2,Z_3}(\tau)+P_{in}\left\langle 1-F_{Z_2}(\Delta t)\right\rangle \delta(\tau), \tag{9}$$

where

$$f_{Z_2,Z_3}(\tau)=\frac{\partial F_{Z_2,Z_3}(\tau)}{\partial \tau}. \tag{10}$$

The moment generating function of $\mathbf{T}_i$ is given by the Laplace-Stieltjes Transform of $f_{\mathrm{T}_i}(\tau)$, evaluated for $-s$:

$$\phi_{\mathrm{T}_i}(s)=\int_0^\infty f_{\mathrm{T}_i}(\tau)e^{s\tau}d\tau = P_{out}e^{s\Delta t}\phi_{Z_1}(s)+P_{in}\int_0^\infty f_{Z_2,Z_3}(\tau)e^{s\tau}d\tau + P_{in}\left\langle 1-F_{Z_2}(\Delta t)\right\rangle. \tag{11}$$

Then, the derivatives of $\phi_{\mathrm{T}_i}(s)$ at s=0 equal the moments of $\mathbf{T}_i$. Thus, the mean and variance of $\mathbf{T}_i$ can be expressed as follows

$$\begin{aligned}
E\{\mathbf{T}_i\} &= \frac{d\phi_{\mathrm{T}_i}(s)}{ds}\Big|_{s=0} = P_{out}\left[E\{\mathbf{Z}_1\}+\Delta t\right]+P_{in}\int_0^\infty \tau f_{Z_2,Z_3}(\tau)d\tau \\
E\{\mathbf{T}_i^2\} &= \frac{d^2\phi_{\mathrm{T}_i}(s)}{d^2s}\Big|_{s=0} = P_{out}\left[E\{\mathbf{Z}_1^2\}+2\Delta t E\{\mathbf{Z}_1\}+(\Delta t)^2\right]+P_{in}\int_0^\infty \tau^2 f_{Z_2,Z_3}(\tau)d\tau \\
Var\{\mathbf{T}_i\} &= E\{\mathbf{T}_i^2\}-E^2\{\mathbf{T}_i\}
\end{aligned} \tag{12}$$

where $E\{\bullet\}$ and $Var\{\bullet\}$ represent, respectively, the expected value and variance operators.

4.3 Connectivity delay analysis in the STIC network

In this section an analytical expression for the cdf of the connectivity delay; $\mathbf{T}_I$, in the Anywhere/Manytime STIC network architecture (STIC-AM) is obtained. The STIC-AM model analysed in this section consist of two spatially non-overlaping but coordinated sets of information nodes operating in a temporal sequential form. In this section, it is considered that the radius of each information node is r_m and that t_{on}=t_{off}, that is, the temporal intermittence factor equals 1/2, and the temporal reuse factor equals 2.

A session attempt can arrive when the current information node (MN within the area of nominal coverage of a given information node) is *on* or when it is *off*. Obviously, when the current information node is *on* (*off*), the adjacent ones are *off* (*on*). Let the random variable $\mathbf{T}_o$ be the time interval from the moment when the session attempt arrives to the time when the current information node switches from the *on* (*off*) state to the *off* (*on*) state. Also, we define the RV $\mathbf{X}$ as the distance (from the session attempt) between the mobile node and the current information node boundary in the direction of user's movement. It is reasonable to assume that $\mathbf{X}$ and $\mathbf{T}_o$ are uniform RVs in the intervals (0, r_m) and (0, t_{on}), respectively.

Given the following events:

C={The session attempt occurs when the current IN is *off*},

D={The MN moves out of the current IN coverage area before it switches to the *on* state | C},

E={When the MN moves into a New IN and it is *on*, the MN does not get access before the IN switches to the *off* state | D},

F={The MN does not get access in the current infocell | D^C}

G={The current IN switches to the *off* state after the MN moves out of its coverage area | C^C},

H={The MN does not get access in the current infocell | G}

I={The MN gets access before the current IN switches to the *off* state | G^C},

J={The current IN switches again to the *on* state before the MN moves out of its coverage area | I^C},

K={The MN does not get access at the current IN coverage area | J},
L={When the MN moves into the IN, it gets access before the IN switches to the *off* state | J^c}, and their respective complements, the cdf of the connectivity delay $\mathbf{T}_I$ can be expressed as follows

$$F_{T_I}(\tau) = P(\mathbf{T}_I \le \tau) = P(\mathbf{T}_I \le \tau | C) \cdot P(C) + P(\mathbf{T}_I \le \tau | C^c) \cdot P(C^c) \tag{13}$$

where

$$P(C) = P_{off} = \frac{t_{off}}{t_{on} + t_{off}},$$

$$P(C^c) = P_{on} = \frac{t_{on}}{t_{on} + t_{off}},$$

$$\begin{aligned} P(\mathbf{T}_I \le \tau | C) = \ & P(D)\left[P(\mathbf{T}_I \le \tau | E) \cdot P(E) + P(\mathbf{T}_I \le \tau | E^c) \cdot P(E^c)\right] + \\ & P(D^c)\left[P(\mathbf{T}_I \le \tau | F) \cdot P(F) + P(\mathbf{T}_I \le \tau | F^c) \cdot P(F^c)\right] \end{aligned}$$

$$\begin{aligned} P(\mathbf{T}_I \le \tau | C^c) = \ & P(G)\left[P(\mathbf{T}_I \le \tau | H) \cdot P(H) + P(\mathbf{T}_I \le \tau | H^c) \cdot P(H^c)\right] + \\ & P(G^c)\Big[P(\mathbf{T}_I \le \tau | I) \cdot P(I) + \\ & P(I^c)\Big\{P(J)\left\langle P(\mathbf{T}_I \le \tau | K) \cdot P(K) + P(\mathbf{T}_I \le \tau | K^c) \cdot P(K^c)\right\rangle + \\ & P(J^c)\left\langle P(\mathbf{T}_I \le \tau | L) \cdot P(L) + P(\mathbf{T}_I \le \tau | L^c) \cdot P(L^c)\right\rangle\Big\}\Big] \end{aligned}$$

Using the involved random variables, equation (13) can be written as follows

$$\begin{aligned} F_{T_I}(\tau) = \ & P_{off}\Big\{F_U(0)\left\langle F_{T_1}(\tau)\left[1 - F_U(-\Delta t)\right] + F_Z(\tau) F_U(-\Delta t)\right\rangle + \\ & \left[1 - F_U(0)\right]\left\langle F_{T_1}(\tau) F_U(\Delta t) + F_{T_o}(\tau)\left[1 - F_U(\Delta t)\right]\right\rangle\Big\} + \\ & P_{on}\Big\{F_U(0)\left\langle F_{T_o}(\tau) F_Z(\Delta t) + \left[1 - F_Z(\Delta t)\right]\right\rangle + \left[1 - F_U(0)\right]\Big\langle\left[1 - F_{T_o}(\Delta t)\right] + \\ & F_{T_o}(\Delta t)\Big(\left[1 - F_U(t_{on})\right]\left[F_{T_1}(\tau)\left[1 - F_U(t_{on} + \Delta t)\right] + F_{T_2}(\tau) F_U(t_{on} + \Delta t)\right] + \\ & F_U(t_{on})\left[F_Z(\tau) F_U(t_{on} - \Delta t) + \left[1 - F_U(t_{on} - \Delta t)\right] F_{T_2}(\tau)\right]\Big)\Big\rangle\Big\} \end{aligned} \tag{14}$$

where, $F_{T_o}(\tau)$, $F_{T_1}(\tau)$, $F_{T_2}(\tau)$, $F_Z(\tau)$, and $F_U(\tau)$, are the cdf of the following random variables: $\mathbf{T}_o$, $\mathbf{T}_1$ (=$\mathbf{T}_o$+t_{on}), $\mathbf{T}_2$ (=$\mathbf{T}_o$+2t_{on}), $\mathbf{Z}$ (=$\mathbf{X}/\mathbf{V}$), and $\mathbf{U}$ (=$\mathbf{Z}$-$\mathbf{T}_o$), respectively. Note that, $\mathbf{T}_1$ and $\mathbf{T}_2$ are uniform RV in the intervals (t_{on}, 2t_{on}) and (2t_{on}, 3t_{on}), respectively (Papoulis & Pillai, 2002). The cdf of $\mathbf{Z}$ is given by equation (2) with a=0, b=r_m, c=v_{min}, and d=v_{max}. Using the methodology described in (Papoulis & Pillai, 2002, page 185) and assuming that $\mathbf{Z}$ and $\mathbf{T}_o$ are independent, it is straightforward to obtain the cdf, pdf, and mgf of $\mathbf{U}$. This task is left to the reader as an exercise.

Finally, as in the case of SIC networks (sub-section 4.2), using de cdf of $\mathbf{T}_I$ given by equation (14), mathematical expressions for the mean value, standard deviation, pdf, and mgf, of this random variable can be obtained.

4.4 Comments on the system capacity loss of STIC networks relative to SIC networks

In STIC networks, information nodes (access points) are available (or active) only for a fraction of time. Hence, their system capacity per spatial area unit[4] (in bps/m^2) of STIC networks is smaller relative to SIC networks. This capacity loss depends mainly on the temporal reuse factor and it is discussed next.

In order to carry out a fair comparison among the performance of STIC and SIC networks, let us assumed that a STIC network is designed in such a way that the amount of interference experienced (determined by the access points separation and channel gain) is the same as that of a reference SIC network[5]. Under these conditions, the capacity in bps (i.e., throughput) of each access point in SIC and STIC networks is the same. However, system capacity per spatial area unit in the STIC network is less than that in the SIC network because of the intermittent operation of its access points. That is, in STIC networks connectivity is available only a fraction of time that depends on the temporal reuse factor. This capacity loss per spatial area unit is the price to pay for the connectivity delay improvement in STIC networks. Nevertheless, depending on the system and design parameters (i.e., infocell length, separation between adjacent infocells, number of sets of information nodes, temporal reuse factor, temporal intermittence factor, etc.), and on the network architecture (i.e., manywhere/manytime or anywhere/manytime STIC configurations), this capacity loss can be acceptable and/or negligible. This asseveration is reinforced by the following facts.

Commonly in mobile wireless communications networks, it is either worthless or inefficient to have system capacity concentrated in only a fraction of the total area where terminals/users freely roam (here referred to as system area). In particular, in SIC networks, if mobile nodes (terminals) in the spatial region where the system capacity is concentrated (or, equivalently, where terminals have connectivity) have not more information to transmit/receive, then the system capacity is wasted and cannot be used to attend terminals in other regions (because of the spatial intermittent connectivity). The probability of occurrence of this event is not negligible due to the fact that terminals always have the necessity to transmit/receive only a limited amount of information (finite number of bits) and that the transmitted/received information is not instantaneously processed (then, the time period between packets generation/request is always greater than zero). Additionally in SIC networks, due to the inherent and fundamental mobility freedom of users' characteristic in mobile wireless communications networks, in general, and because of the random nature of the time instants when users generate (request) information; it is not unlikely that terminals require to transmit (receive) information in zones where there is not connectivity (Cavalcanti et al., 2002; Chowdhury et al., 2010)). Then, because of the

[4] System capacity per unit area refers to capacity in bps/m^2 considering the total area where terminals/users freely roam.

[5] In a homogeneous environment, this can be achieved by keeping the access points separation equal in SIC and STIC networks, as explained in (Hernández-Valdez & Cruz-Pérez, 2008). Please note that intertmittstations architecture proposed in (Hernández-Valdez & Cruz-Pérez, 2008) to achieve continuous connectivity is a particular case of a STIC network.

inhomogeneous spatial capacity distribution in SIC networks, it is possible that some spatial areas have more capacity than the necessary and other zones do not have capacity at all.
The quantitative comparison of SIC and STIC networks in terms of its capacity is a subject of further future research. Nevertheless, as explained above, it is expected that the system capacity loss of STIC networks relative to SIC networks be significantly smaller to the fraction of time that the access points are active (i.e., inverse to the temporal reuse factor). This is particularly true for uniform spatially distributed traffic demand systems with non-interactive service classes[6]. For mobile wireless communications with interactive services, the capacity loss of STIC networks relative to SIC networks could be reduced with the use of *adaptive temporal reuse factor*. Basically, in scenarios with non-uniform spatial distribution traffic, in general, access points in regions where there is larger capacity demand could be adaptively activated a larger fraction of time (*adaptive temporal reuse factor*). The impact of both the non uniformity in the spatial traffic distribution caused by the correlation of traffic demand with users' position, and the use of *adaptive temporal reuse factor* in intermittent connectivity networks needs to be evaluated and it is also a topic of further future research.
More importantly, because of its smaller connectivity delay, a fundamental advantage of STIC networks relative to SIC networks is their capability to support more delay constrained services. Then, the price to pay in terms of capacity loss could be acceptable and/or insignificant.

5. Performance evaluation

The goal of the numerical evaluations presented in this section is to compare in terms of connectivity delay drive-through SIC and STIC networks. For the numerical evaluations, typical values for the users' velocity pdf are used (El-Dolil et al., 1989). In the following figures, the labels UN and TN stand for uniform distribution and truncated normal distribution of the pdf of users' velocity, respectively. As stated before, SIC networks are based on ultra-high speed radios transmitting to very small and discontinuous zones of coverage through which the users pass by a few seconds and, in general, the distance between zones of coverage is much greater than the information node radius (Cavalcanti et al., 2002; Frenkiel et al., 2000).
Figs. 3.a and 3.b show, respectively, the cdf of $\mathbf{T}_i$ and $\mathbf{T}_I$ with c=11.11 m/s, d=44.44 m/s, μ_t=27.77 m/s, and σ_t=5.55 m/s. In Fig. 5.a Δt=0.05 s, with r_s=l as a parameter. In Fig. 5.b Δt=0.1t_{on} s, r_m=250m, with t_{on} as a parameter. Figs. 6.a and 6.b show, respectively, the pdf of $\mathbf{T}_i$ and $\mathbf{T}_I$ with c=11.11 m/s, d=44.44 m/s, Δt=0.05 s, l=600 m, and r_s=250 m, with the mean and standard deviation of the pdf of the velocity of mobile nodes as parameters. The delta function given by the last term on the right of (9) is not plotted in any curve of Fig. 6 and, the value of this term is equal 0.497δ(τ) and 0.451δ(τ) for all the plots of Figs. 6.a and 6.b, respectively. The coefficient of the delta function does represent the proportion of session

[6] In the interactive class of services (the interactive class supports services typically supported by today's best effort IP networks, including file transfer, web browsing, or telnet applications), the reception of information can trigger the generation/request of new or additional information to be transmitted/received. Due to the fact that the transmission and reception in SIC networks can only occur in spatial regions where there is connectivity, traffic demand in SIC networks with interactive services is correlated with users' position. Then, it is expected that the spatial traffic distribution in a homogeneous SIC network with interactive services be non uniform.

attempts with connectivity delay equals 0 seconds. The following important observations can be extracted from Figs. 5 and 6. The connectivity delay in SIC networks depends strongly on the distance between zones of coverage (*l*), the type of pdf velocity (uniform or truncated normal), and the parameters of the pdf velocity (mean, variance, maximum speed *d*, and minimum speed *c*). On the other hand, the information node radius has a minor effect on connectivity delay. On the contrary, in STIC networks the connectivity delay is not sensitive to the pdf of mobile nodes' velocity.

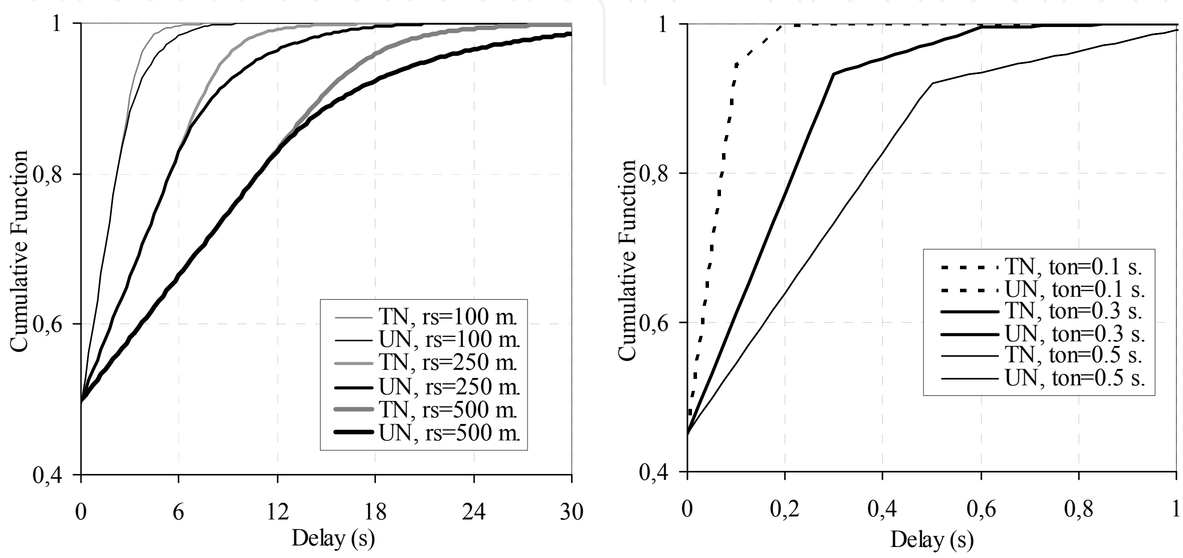

Fig. 5. cdf of the connectivity delay for a one-dimensional (a) SIC network with Δt=0.05 s, and r_s=l as a parameter, (b) STIC network with l_m=0 m, Δt=0.1t_{on}, r_m=250 m, and t_{on} as a parameter

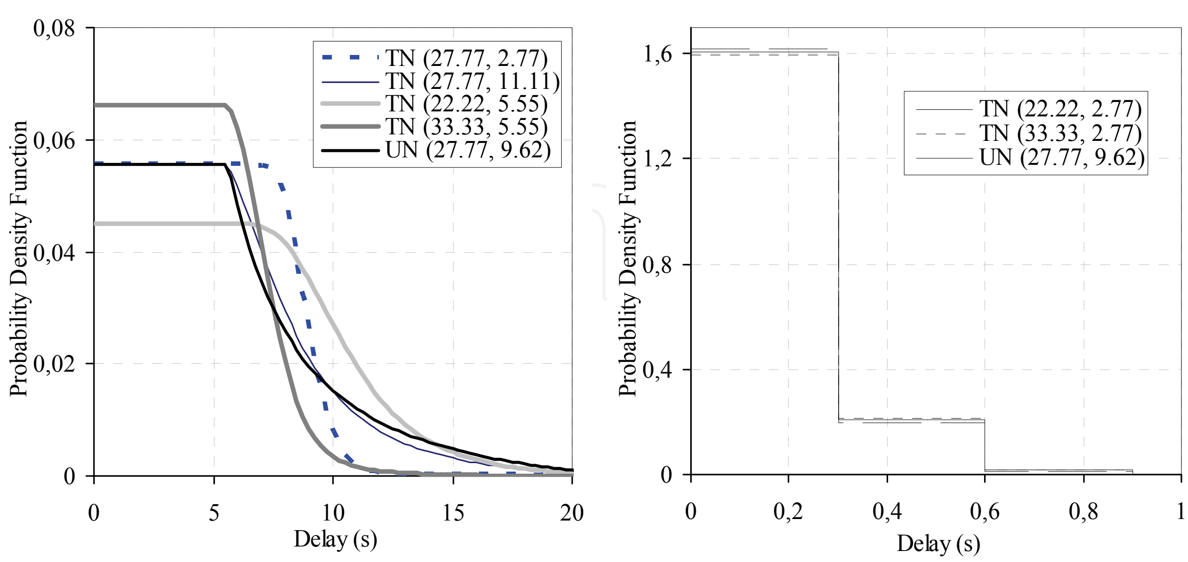

Fig. 6. pdf of the connectivity delay for a one-dimensional (a) SIC network with, r_s=l =250 m, (b) STIC network with l_m=0 m, t_{on}=0.3 s, r_m=250 m, and the mean and standard deviation of pdf velocity as parameters. In both systems Δt=0.05 s

Table 1 shows the mean (μ_{Ti}) and the standard deviation (σ_{Ti}) of the connectivity delay for the SIC network with Δt=0.05 s and v_{min}, v_{max}, r_s, and l, as parameters. On the other hand, Table 2 shows the mean (μ_{TI}) and the standard deviation (σ_{TI}) of the connectivity delay for the STIC network with v_{min}=60 km/h, v_{max}=140 km/h, and r_m=250 m, with Δt and t_{on} as parameters.

(v_{min}, v_{max}) (km/h)	**r_s=l=100 m**		**r_s=l=250 m**		**r_s=l=500 m**	
	μ_{Ti}	σ_{Ti}	μ_{Ti}	σ_{Ti}	μ_{Ti}	σ_{Ti}
(80, 180)	0.77	1	1.9	2.5	3.7	4.9
(80, 120)	0.95	1.2	2.3	3	4.6	6
(40, 120)	1.3	1.7	3.1	4.3	6.2	8.6
(40, 180)	1	1.5	2.5	3.6	4.9	7.2

Table 1. Mean value and standard deviation of Connectivity Delay in the SIC Network. All the values are given in seconds (s)

Δt	**t_{on}=1 ms**		**t_{on}=10 ms**		**t_{on}=100 ms**	
	μ_{TI}	σ_{TI}	μ_{TI}	σ_{TI}	μ_{TI}	σ_{TI}
$0.01t_{on}$	0.26	0.41	2.6	4.1	26	42
$0.1t_{on}$	0.33	0.51	3.3	5.1	33	52
$0.3t_{on}$	0.5	0.65	4.8	6.5	49	67

Table 2. Mean value and standard deviation of Connectivity Delay in the STIC Network. All the values are given in milliseconds (ms)

From Table 2, it is observed that the mean and standard deviation of the STIC connectivity delay are as small as t_{off} is and their values increase as Δt increases. Notice that in STIC networks t_{on} is a design parameter. On the other hand, Table I shows that, in SIC networks, μ_{Ti} and σ_{Ti} are very sensitive to both the distance between zones of coverage and the parameters of the pdf velocity. Finally, from Tables I and II, it is evident that the values of the mean and standard deviation of the connectivity delay in STIC networks are to a great extent smaller than those presented in SIC networks. Then, STIC networks support more restrictive delay sensitive applications than those supported by SIC networks. More importantly, STIC networks offer network designers control and flexibility over the degree of delay and disruption tolerance that intermittent connectivity systems can achieve. Due to this flexibility, STIC networks are intended to provide wireless communication services in a variety of different environments, including highways, hot spots in urban zones, airports, city centres, business districts, tourist zones, etc.

6. Conclusion

This Chapter focused on the delay coverage study in wireless communication networks with intermittent connectivity. Special emphasis was made in spatial and spatial/temporal intermittent connectivity paradigms. We stated that the tremendous growth in demand for wireless mobile multimedia services claims for the development of new techniques and/or network architectures to support the delay requirement of the real-time and/or conversational/streaming part of these applications. With this in mind, the *spatial and temporal intermittent connectivity* (STIC) paradigm was proposed in the literature. STIC networks were conceived to improve system performance in terms of both delay and service disruption probability relative to and without sacrificing the main advantages of spatial intermittent connectivity (SIC) networks (i.e., low cost and low power access to high data rate information services). This is achieved at the expense of a negligible and/or acceptable system capacity per area unit reduction. This capacity reduction of STIC relative to SIC networks depends mainly on the spatial distribution of mobile nodes, spatial reuse factor, *temporal reuse factor*, and *temporal intermittence factor*. The STIC paradigm consists of one or more non-overlapping and coordinated sets of information nodes operating in a temporal intermittent and sequential fashion. This temporal sequential operation mode allows STIC systems to spatially distribute the total system capacity. Then, the STIC network model gives network designers more control and flexibility over both the degree of delay and disruption tolerance that intermittent connectivity systems claim. By allowing the designers to choose the most important parameters to constrain, the model effectively improves both delay and disruption probability at the expense of slight system capacity per unit area reduction. Although, our results are extracted for particular scenarios, with a certain set of parameters values, the contribution clearly and directly quantify the connectivity delay improvement of STIC networks relative to SIC networks. Further research in this topic includes exploring the impact of both the non uniformity in the spatial traffic distribution caused by the correlation of traffic demand with mobile users' position, and the use of *adaptive temporal reuse factor* in STIC networks.

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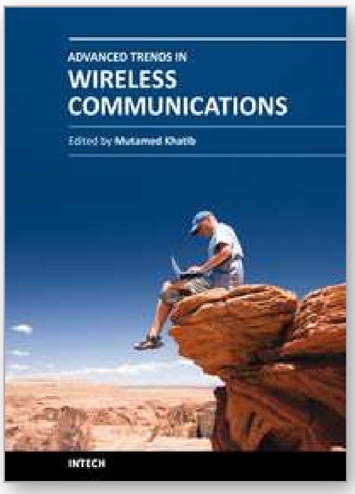

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Physical limitations on wireless communication channels impose huge challenges to reliable communication. Bandwidth limitations, propagation loss, noise and interference make the wireless channel a narrow pipe that does not readily accommodate rapid flow of data. Thus, researches aim to design systems that are suitable to operate in such channels, in order to have high performance quality of service. Also, the mobility of the communication systems requires further investigations to reduce the complexity and the power consumption of the receiver. This book aims to provide highlights of the current research in the field of wireless communications. The subjects discussed are very valuable to communication researchers rather than researchers in the wireless related areas. The book chapters cover a wide range of wireless communication topics.