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Abstract

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Impact of Mobility on the Behavior of Interference in Cellular Wireless Networks*

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Abstract— **In this study, the impact of mobility is investigated in low–speed environments such as femtocells and picocells for wireless networks. Given that there is interference on the uplink of a FDD system, this study solely focuses on how interference evolves with respect to mobility of terminals which move in a random fashion. Wiener–Lévy process is used as a stochastic tool for characterizing the impact of mobility on the future behavior of interference. The results show that there is a trade–off between short and long interference observation (measurement) interval. On the one hand, choosing a short interval leads to a waste of processing power, since the interference level to be observed is not expected to deviate drastically from the previous observations. Choosing a long interval, on the other hand, increases the variance of the density of future interference level. In addition, results show that if there is more than one interference source in motion, the interference level observed has a tendency to increase in the future in low mobility environments. It is also shown that mean value of the interference level density to be observed in the future increases, whereas its standard deviation decreases with respect to the number of interference sources in motion.**

Index Terms— **frequency division duplexing, interference, mobility, Wiener–Lévy process**

I. Introduction

It is expected that next generation cellular systems will be designed to meet the needs for high–speed data and multimedia transmission as well as high capacity voice support. In order for next generation cellular systems to satisfy all these needs, there are some requirements to be met which include: support for wider and scalable bandwidths; support for advanced antenna systems (including multiple–input multiple–output (MIMO)); increased peak data rates; increased capacity and spectral efficiency; improved latency; better resource management; better coverage; advanced interference management (including advanced interference mitigation techniques and flexible resource allocation), and so on.

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Many of the above requirements one way or another are related to handling interference. One of the dominant sources of interference is co–channel interference (CCI) in cellular wireless communication systems. It limits capacity, peak data rates, coverage, and transceiver performance. Traditionally, in cellular systems, CCI is controlled by introducing the "re–use" of the frequencies in distant cells (large cluster sizes or reuse factors) at the expense of reducing the capacity, such as in the case of Global System for Mobile (GSM) [1, 2]. Re–using frequencies in all the adjacent cells, namely frequency re–use of one (FRO), is desirable in increasing the capacity and spectral efficiency. Furthermore, FRO also means that there is no need for frequency planning. However, FRO causes significant CCI especially in the vicinity of the cell borders [3]. Dynamically coordinating the transmission from multiple sources can control the CCI [4–6]. Therefore, FRO and extended adaptation capabilities to dynamic conditions are very essential concepts for next generation wireless networks [7–9]. Since interference is a very dynamic phenomenon, the success of the adaptation of next generation wireless networks depends on being aware of the factors affecting it. Considering that interference is affected by many factors such as space, time, frequency, and power, being aware of interference requires a careful investigation of the impacts of these factors.

In this study, the impact of mobility, which is a function of both space and time, on interference is investigated in low mobility environments such as femtocells and picocells for wireless networks. An uplink interference scenario is studied for frequency division duplexing (FDD) systems in the presence of low–speed mobiles. Interference is solely considered as a function of mobility of interfering sources; other impairments such as small–scale fading and shadowing are not taken into account for the sake of a simpler analysis. Wiener–Lévy process is used as a stochastic tool for characterizing the impact of mobility on the future behavior of interference. The remainder of the paper is organized as follows: Section II introduces the main assumptions, whereas Section II-A discusses the relationship between mobility and interference, and Section II-B outlines the interference model considered. Section III presents the numerical results. In Section IV final remarks are provided.

II. Mobility and Interference

In this study an uplink transmission for a FDD system is considered. An example scenario is illustrated in Figure 1. In this scenario, assume that UE_2 is in the vicinity of the cell border and moves in a random fashion at a speed of an average pedestrian. In order to analyze solely how the interference evolves in time with respect to the motion, assume that the interfering signal undergoes only distance dependent path loss. Moreover, power control is employed in the cell in which UE_2 resides in such a way that received power at the base station is constant. The cells are assumed to be of identical size, *i.e.*, $r_1 = r_2 = r$ where r_c is the radius of c–th cell with $c \in \{1, 2\}$. The displacement of UE_2 is considered in terms of only two directions: either toward the victim, or away from the victim.[1] Under these assumptions, a mobility model will be formed subsequently in order to investigate its impact on interference.

A. Mobility Model and Wiener–Lévy Process

For low–speed environments such as picocells and femtocells, one of the popularly used mobility models is random walk. Random walk is a reasonable model for these sorts of environments due to the following two reasons: First, random walk is a very well known stochastic tool which can represent the displacement of mobiles for several different scenarios. For instance, standard random walk represents the maximum uncertainty about the direction of the motion of mobiles, whereas the generalized version can be used in modeling a broader class of motion behaviors such as the motion of groups and/or clusters. Second, changing the direction of motion is very likely in low mobility scenarios especially when the random movements of pedestrians are of particular interest. However, this sort of behavior might not be realistic in high–speed scenarios, since the high–speed mobiles cannot change their direction during their motion as fast as low–speed mobiles.

In the generalized random walk, a mobile moves along a straight line. In the scenario considered in this study, the straight line corresponds to the line which connects the victim and source. At every observation instant, the mobile (*i.e.*, the source of interference) either moves toward or away from the victim at a constant speed $|\vec{v}|$ throughout the motion. In order to generalize such a scenario, assume that the mobile moves toward the victim with a probability of p and away from the victim with a probability of q where $p + q = 1$. Hence, the motion can formally be captured by a random process $\{X_t\}$ where the position of the mobile, S, at time instant $t = K\Delta t$ for the K–th step of the process is given by a random variable $S_t = \sum_{k=1}^{K} B_k \Delta t$ where $\Pr(B_k = |\vec{v}|) = p$ and $\Pr(B_k = -|\vec{v}|) = q$, and B_k is unit magnitude of the displacement along with direction information. With these assumptions, it is easy to verify that $E\{S_t\} = (p-q)K|\vec{v}|\Delta t$ and $\sigma^2_{S_t} = 4pqK\left(|\vec{v}|\Delta t\right)^2$ where $E\{\cdot\}$ denotes the statistical expectation and $\sigma_{(\cdot)}$ is the standard deviation of their input, respectively.

Note that random walk defines a stochastic process of motion for a single unit in terms of discrete intervals, which are called “steps.” However, in a generalized interference scenario such as the one examined in this study, the total interference might be formed by more than one unit (*i.e.*, source of interference). Therefore, the total interference needs to be evaluated by allowing for overall displacement of the ensemble of sources. Moreover, since the mobile radio propagation environment is highly dynamic, the observation interval should be kept as short as possible. This forces the random walk model to be considered in the limiting case where the impact of total displacement is evaluated for very short intervals, Δt. Hence, the limiting case of random walk, which is called “Wiener–Lévy process,[2]” can be used as a reference model. In standard Wiener–Lévy process, the process $\{X_t;\ t \geq 0\}$ is a normal process for $\Delta t \to 0$ and $\Delta x \to a\sqrt{\Delta t}$ where a is some constant. In order for a process to be called standard Wiener–Lévy process, the following three properties (**P**) need to be satisfied [10]: (**P**.I.) $X_t \in \mathbb{R}$ and $X_0 = 0$, (**P**.II.) $E\{X_t\} = 0$, (**P**.III.) the increments $X_{t_1} - X_{t_2}$ are independent and stationary along with $E\left\{(X_{t_1} - X_{t_2})^2\right\} = b\,(t_1 - t_2)$ where b is some constant (*i.e.*, they all depend only on $(t_1 - t_2)$). Note that (**P**.II.) (and consequently (**P**.III.)) can be modified according to the model adopted, as discussed in Section II-A.

B. Impact of Mobility on Interference

Let $\Delta I(K)$ be the rate of change of interference observed by the victim and defined as:

$$\Delta I(K) = \frac{I(K)}{I(K-1)} \tag{1}$$

where K is the observation index with respect to time such as $t = K\Delta t$ and Δt is the observation interval defined in Section II-A and $I(K)$ denotes power spilled over the victim by the source UE_2. The direct consequence of (1) is:

$$I(K) = I_0 \prod_{k=1}^{K} \Delta I(k) \tag{2}$$

where I_0 is the constant which represents the initial interference $I(0)$.

[1] This assumption can be generalized very easily, since the velocity $\vec{v}$ of UE_2 can always be projected onto the straight line which connects the source and the victim for any point in Euclidean space.

[2] This process is also known as “Brownian motion.”

Assume that UE_2 moves with a velocity $\vec{v}_2$ in the standard random walk form. Therefore, the displacement after one unit of observation interval is $\Delta d_S = \mp|\vec{v}|\Delta t$ which includes also the direction information. Due to the power control relationship:

$$P = \frac{P_S(k-1)}{(d_S)^n} = \frac{P_S(k)}{(d_S + \Delta d_S)^n} \tag{3}$$

is obtained where n denotes the path loss exponent for the environment of interest. Thus, as in (1), the change can be expressed as:

$$D(k) = \frac{P_S(k)}{P_S(k-1)} = \left(1 + \frac{\Delta d_S}{d_S}\right)^n \tag{4}$$

where $D(k)$ denotes the ratio between the two consecutive transmitted power levels of the interference source, namely, UE_2.

Recall that in this scenario, interference spilled over the victim varies with time due to the motion of UE_2. As UE_2 moves, distance between the source and victim changes. In addition, since a power control regime is employed, transmit power of UE_2 changes as well. If the rate of change of interference is considered, it yields:

$$\Delta I(k) = \frac{\frac{P_S(k)}{(2r-d_S)^n}}{\frac{P_S(k-1)}{(2r-(d_S-\Delta d_S))^n}} = D(k)\left(1 + \frac{\Delta d_S}{2r - d_S}\right)^{-n} \tag{5}$$

Note that the rate of change, $\Delta I(k)$, forms a stochastic process which is actually governed by another stochastic process, the displacement. Recall that both $D(k)$ and the second term at the right hand side of (5) are governed by the same normal process in different scales. However, the overall process exhibits an exponential behavior because of n. Therefore, considering the mathematical tractability, additive notation can be considered rather than multiplicative one. By applying the logarithm operator $\ln(\cdot)$ to (2), the following reads:

$$\ln(I(K)) = \ln(I_0) + \sum_{k=1}^{K} \ln(\Delta I(k)) \tag{6}$$

where

$$\ln(\Delta I(k)) = \ln(D(k)) - n \ln\left(1 + \frac{\Delta d_S}{2r - d_S}\right) \tag{7}$$

In (7), the natural logarithm of the stochastic process ΔI, that is $\ln(\Delta I(\cdot))$, represents a random variable which is the difference of two log–normal random variables at a specific observation instant k. However, the two terms to the right of (7) depend on each other; therefore, approximation of sum of the two terms with the aid of methods presented in [11, and references therein] does not hold.[3] Even though there is no closed–form solution for the "dependent" process in (7), statistically, it is still possible to estimate the behavior of (6). Since $\Delta I(\cdot)$s are assumed to be independent of each other and identically distributed due to the Wiener–Lévy process, for $K \to \infty$, the summation in (6) will converge to normal distribution because of the central limit theorem. However, as $K \to \infty$, again, due to the modified Wiener–Lévy process introduced in Section II-A, the variance will diverge as well. This implies that if the observation interval is kept very long, the interference power to be spilled over the victim might be very far away from the value observed in the previous step. Conversely, if the interference observation is kept very short (*i.e.*, $K \to 0$), the interference power is not expected to be very different from the previous observation due to small displacements; hence, it will waste the processing power of the system.

In addition to the K value, the number of mobile interfering sources, namely H, must also be taken into account. Since the total interference power spilled over the victim is actually the sum of individual interference power levels spilled by each mobile source, generalized version (*i.e.*, $H \geq 1$) is obtained by modifying (5) as follows:

$$\Delta I^{(H)}(k) = \frac{\sum_{h=1}^{H} \frac{P_S^h(k)}{(2r-d_S^h)^n}}{\sum_{h=1}^{H} \frac{P_S^h(k-1)}{(2r-(d_S^h-\Delta d_S^h))^n}} \tag{8}$$

Since (8) is mathematically intractable, its behavior will be investigated via the simulations.

III. Numerical Results

In simulating the scenario introduced in Section II, several cases are considered. In the simulation set, each individual scenario is simulated 10000 times in order to obtain reliable statistics. All the sources are distributed uniformly over the interval of $[1.2r, 1.5r]$, where the position of the victim base station is chosen as origin for the sake of brevity. This interval is chosen in order to represent the sources which reside in the vicinity of their own cell. None of the sources is allowed to be handed over the neighboring cell. Therefore, during the simulations number of mobile interference sources is fixed.. Some other general parameters used in the simulations are given in Table I.

In order to show the behavior of the model, first the simplest case, single interference source (*i.e.*, $H = 1$) is considered. In this scenario, $K = 15$ and $I_0 = -7$dBm.

[3]It is important to recall that the probability density function (PDF) of the sum of two independent and identically distributed two random variables is obtained by convolving the individual PDFs with each other, whereas that of the difference is obtained by cross–correlating the individual PDFs with each other. Since PDFs of interest are even functions, summation and difference are essentially the same for the case considered here.

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TABLE I
COMMON PARAMETERS USED IN SIMULATIONS

Parameters	Values Used
Path loss exponent	$n = 4$
Number of sources	$H = \{1, 5, 10, 20\}$
Speed of mobiles	$\|\vec{v}\| = 3m/s$
Cell radius	$r = 30m$
Maximum number of steps	$\max(K) = 15$
Unit observation duration	Δt =1s

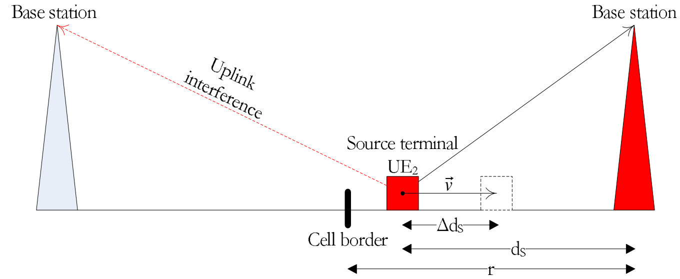

Fig. 1. Illustration of an interference scenario for an uplink transmission in an FDD system during a unit observation interval Δt. In this scenario the source is denoted by UE_2, whereas the victim is the base station on left hand side.

As illustrated in Figure 2, due to a high K value, the distribution converges to the normal distribution with $\mu_{K=15} = -4.77$dBm and $\sigma_{K=15} = 8.25$dBm. For the same simulation setup, when $K = 5$, the statistics are $\mu_{K=5} = -4.68$dBm and $\sigma_{K=5} = 4.58$dBm; and when $K = 10$, $\mu_{K=10} = -4.67$dBm and $\sigma_{K=10} = 6.62$dBm. As stated in Section II-B, the mean value of $I(K)$ does not vary significantly, since the statistical expectation of the displacement is zero. However, when the observation interval increases, σ changes significantly, because the displacement of the source becomes significant.

As the second stage of the simulations, the number of sources is increased in order to see the impact of mobility on behavior of the interference under such scenarios. In order to investigate this, the same scenario above is simulated for $K = 15$ along with $H = 20$ and $I_0 = 6.06$dBm. The results are presented in Figure 3. For the results illustrated, the statistics obtained are $\mu_{K=15} = 11.38$dBm and $\sigma_{K=15} = 4.01$dBm. Note that there is a significant increase in the mean value, whereas a drastic drop is experienced in the standard deviation compared to those of single source cases. This totally stems from the number of interferers, because after a long observation period, it is very likely to find some of the sources placed close to the cell border. As expected, having a larger number of interfering sources close by will create a higher interference level compared to that of single source case.

For comparison purposes, an ensemble of different environments in which there are different number of mobile terminals in the source cell is simulated as well. The results are given in Figure 4 and Figure 5. Figure 4 plots the evolution of the mean of the future interference levels versus observation interval K. In Figure 4, the information is hidden in the slopes of the curves, since the intercept values change for different initial conditions I_0 as stated in (6). Note that for single source case (*i.e.*, $H = 1$), the mean value does not change at all. This stems from the fact that when $H = 1$, statistically, the total displacement of the source is zero as stated in Section II-A for $p = q$. However, when the number of sources increases (*i.e.*, $H > 1$), there will be some mobile terminals which are closer to the victim. Therefore, all of the curves for the set $H = \{5, 10, 20\}$ have positive slopes. Figure 5 plots the evolution of the standard deviation of the future interference levels versus observation interval K. Note that the standard deviation increases with K in a quadratic form as expected due to the Wiener–Lévy process.

IV. DISCUSSION AND FINAL REMARKS

In this study, the impact of mobility on interference is investigated in low–speed environments such as femtocells and picocells for next generation wireless networks. This study solely focuses on how mobility affects the evolution of interference in time in these sorts of environments in the presence of mobile terminals which move in a random fashion for an uplink in a FDD system.

The results show that the interference level to be observed in the future has a tendency to increase in low mobility environments except for single mobile interference source. In addition, for $p = q$ the mean value of the interference level density to be observed in the future increases, whereas its standard deviation decreases with respect to the number of interference sources in motion. It is also seen that mobility leads to a trade–off between long and short observation interval K. If $K \to \infty$, no matter how many interference source exists, the standard deviation of the future interference level increases quadratically. However, the minimum standard deviation is obtained when the number of mobile interference sources is maximum for any fixed K.

If modified Wiener–Lévy process is considered for $p \neq q$, then the mean value of the interference observed increases/decreases significantly depending on the direction of the mobility which is defined by p. This modified version also corresponds to the case in which the sources move in a regular basis rather than a random one. Note that any limiting case (*i.e.*, either $p \to 1$ or $q \to 1$) represents the motion of a group of sources which exhibits a structured movement rather than totally independent, random individual movements.

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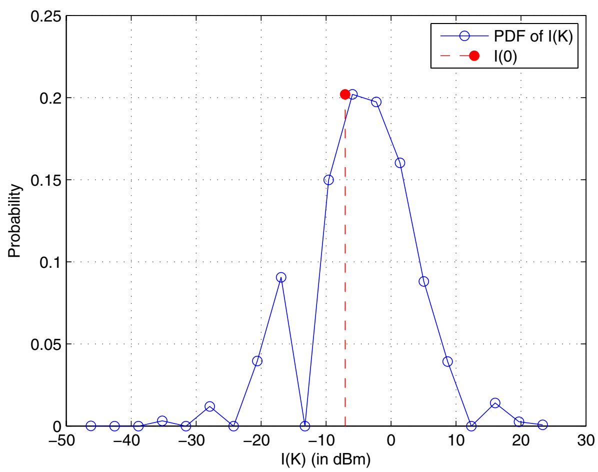

Fig. 2. PDF of the future interference levels to be observed where there is only one source ($H = 1$) following Wiener–Lévy process along with $p = q$, $I(0)$, and $K = 15$.

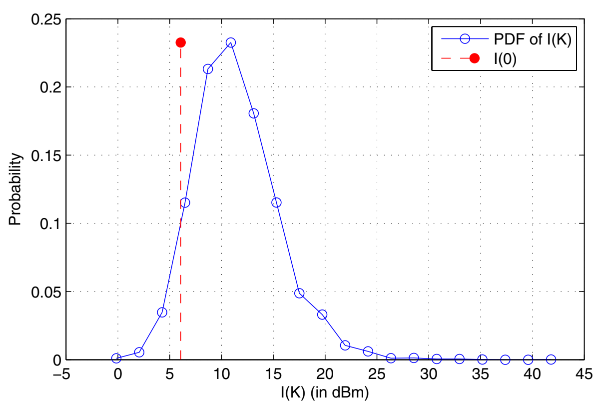

Fig. 3. PDF of the future interference levels to be observed where there are twenty sources ($H = 20$) following Wiener–Lévy process along with $p = q$, $I(0)$, and $K = 15$.

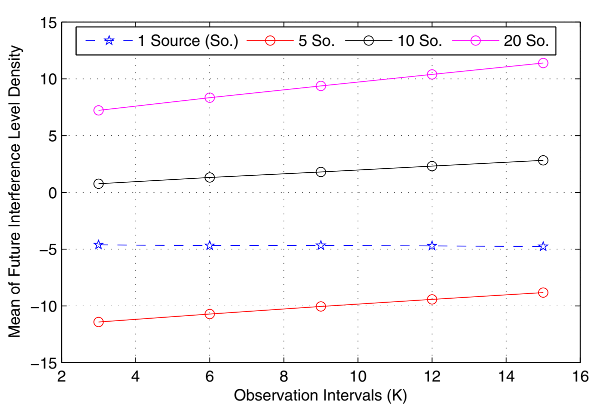

Fig. 4. Mean values of PDF of the future interference levels to be observed where $H = \{1, 5, 10, 20\}$ following Wiener–Lévy process along with $p = q$, and $\max(K) = 15$.

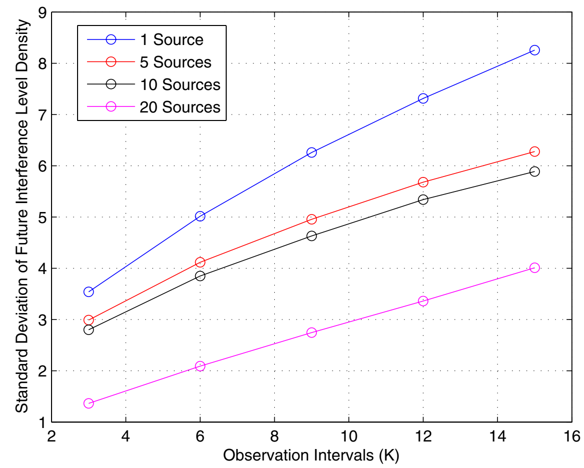

Fig. 5. Standard deviation values of PDF of the future interference levels to be observed where $H = \{1, 5, 10, 20\}$ following Wiener–Lévy process along with $p = q$, and $\max(K) = 15$.

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