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Two-step procedures in Palm theory

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Abstract

Random time changes (RTC's) are right-continuous and non-decreasing random functions passing the zero-level at 0. The behavior of such systems can be studied from a randomly chosen time-point and from a randomly chosen level. From the first point of view the probability characteristics are described by the time-stationary distribution $P$. From the second point of view the detailed Palm distribution (DPD) is the ruling probability mechanism. The main topic of the present paper is the relationship between $P$ and its DPD. Under $P$, the origin falls in a continuous part of the graph. Under the DPD, there are two typical situations: the origin lies in a jump-part of the extended graph or it lies in a continuous part. These observations lead to two conditional DPD’s. We derive two-step procedures which bridge the gaps between the several distributions. One step concerns the application of a shift, the second is just a change of measure arranged by a weight-function. The procedures are used to derive local characterization results for the distributions of Palm type. We also consider simulation applications. For instance, a procedure is mentioned to generate a simulation of the RTC as seen from a randomly chosen level in a jump-part when starting with simulations from a randomly chosen time-point. The point process with batch-arrivals is often used as an application.
1 Introduction

Palm theory for queues and point processes (PP’s) studies the relationship between two probability mechanisms. Intuitively, the first - the time-stationary distribution $P$ - describes the probability behavior of random phenomena within the (queueing) system as it is seen from a randomly chosen time-point. The second, the Palm distribution (PD) $P^0$, describes this behavior as it is seen from a randomly chosen occurrence (often an arriving customer). See, e.g., Franken et al. (1981), Baccelli and Brémaud (1994), or Sigman (1995) for a review. An important part of this Palm theory considers the direct relationship between the distributions $P$ and $P^0$ themselves. For instance, in Theorem 1.3.1 of Franken et al. (1981) the local characterization of the PD of a simple point process is formulated. Intuitively this approximation theorem expresses that in a sense $P^0$ can be considered as the conditional distribution of $P$ given an occurrence in the origin.

In Nieuwenhuis (1994) it is proved that this local characterization is uniform and the rate of convergence is studied. Also, a two-step procedure is given to transform $P$ into $P^0$ (or vice versa). (See also Thorisson (1995) and Nieuwenhuis (1998)). Essentially, $P^0$ arises from $P$ by first shifting the origin to the last occurrence before it and then changing the importance of the realizations by a weight function. The first step is based on a shift, the second on a change of measure. This change of measure follows from Theorem 2.1 in Nieuwenhuis (1989) where distributions are introduced which have the same null-sets as the PD and which can serve as a bridge between $P$ and $P^0$. As an immediate consequence of the simulation procedure in Section 14 of Thorisson (1995), this theorem gives the opportunity to obtain a simulation from $P^0$ when starting with simulations from the distribution $P$, in the case that the interarrival times are bounded away from zero.

During the recent years the development of Palm theory has advanced. In Schmidt and Serfozo (1995) an overview is given of Palm theory for random measures. In Miyazawa and Schmidt (1997) Palm theory is applied in the context of risk processes, while Miyazawa (1994) considers fluid queues. In Miyazawa et al. (1998) a general view on Palm theory is presented by considering the random phenomenon of interest as a right-continuous and non-decreasing random function passing the zero-level at zero, i.e. as a random time change (RTC). This theory not only includes Palm theory for random measures, but also includes the theory for non-simple queueing systems and fluid queues with general jumps. For an RTC $\Lambda$ two distributions of Palm type are considered. The detailed Palm distribution (DPD) of $\Lambda$ is the most important one in the sense that, for instance, the ordinary Palm distribution (OPD) can immediately be obtained
from it. Intuitively the DPD of $\Lambda$ arises by another random-choosing procedure: choose a level at random on the vertical axis and shift the origin to the corresponding position on the extended graph of $\Lambda$ (i.e., the graph extended with the jump-parts).

In view of the advances of Palm theory for simple PP's via Palm theory for random measures to Palm theory for general RTC's, it is natural to study the generalizations of specific results like the local characterization theorem, the two-step procedure and the simulation procedure. Especially these are interesting because they will give a better understanding of rather new concepts like the DPD. In the present research we will consider such generalizations for the DPD (and also the OPD) of RTC's. For the larger part we will assume that the probability that the random function $\Lambda$ (or its generalized inverse) makes jumps is positive.

In Section 2 we will formulate the framework that is used. Some known results, needed for the present research, are repeated. Under the DPD, there are two typical types of realizations of the RTC. For the first type the origin lies in a jump-part of the extended graph, for the second type in a continuous part. So, the DPD is a mixture of two conditional DPD's. In two lemma's we study independencies under the several distributions. In Section 3 we derive several relations which express easy transitions from one distribution to another. Essentially, they express transformations by a two-step procedure. One step concerns a shift of the origin. The other step changes the importance of the realizations by way of a weight function and just means a change of measure. Emphasis will be on transition from $P$ to the two conditional DPD's. The topic of Section 4 is how to approximate one distribution under the regime of another. For instance in the case that $P$ is the ruling distribution, we derive local characterization of the conditional DPD's. The limit results turn out to be uniform. As an application, we also consider local characterization of Palm probabilities in the case of an arrival process with batches. In Section 5 we apply the results of Sections 3 and 4 by considering simulation procedures. For instance, a version of the RTC as seen from a randomly chosen level in its jump-parts can be derived from versions as seen from a randomly chosen time-point. Again, things are considered for a point process with batch-arrivals.

2 Preliminaries

Let $(\Omega, F)$ be a measurable space supporting the right-continuous, non-decreasing random function $\Lambda$ on $\mathbb{R}$ for which

$$\lim_{t \to \pm \infty} \Lambda(t) = \pm \infty \quad \text{and} \quad \Lambda(0-) \leq 0 \leq \Lambda(0)$$
for all $\omega \in \Omega$. We call $\Lambda$ a random time change, RTC for short. The extended graph $\Gamma(\omega)$ of $\Lambda(\cdot, \omega)$ is the subset of $\mathbb{R}^2$ consisting of the graph of $\Lambda(\cdot, \omega)$ supplied with the vertical jump-parts. In practice often the canonical setting is considered. That is, $\Omega$ is taken as the set $G$ of all right-continuous and non-decreasing functions $g : \mathbb{R} \to \mathbb{R}$ with $\lim_{t \to \pm\infty} g(t) = \pm \infty$, passing the zero-level at zero. We will, however, consider the general, abstract set-up.

We will always assume that a family $\Theta = \{\Theta(t, x) : (t, x) \in \mathbb{R}^2\}$ of transformations exists - possibly on a larger measurable space $(\tilde{\Omega}, \tilde{\mathcal{F}})$ - in such a way that the (random) extended graph $\Gamma$ of $\Lambda$ is consistent with $\Theta$, and that the family $\Theta$ behaves on $\Gamma$ like a group. I.e., we assume that:

(i) For all $\omega \in \Omega$, $(t, x) \in \Gamma(\omega)$ and $(s, y) \in \Gamma(\Theta(t, x)\omega)$ we have

(a) $\Lambda(\cdot, \Theta(t, x)\omega) = \Lambda(t + \cdot, \omega) - x$,
(b) $\Theta(s)\Theta(t, x)\omega = \Theta(s + t, x + y)\omega$.

Note that in the canonical setting this assumption is trivially satisfied: just take $\tilde{\Omega}$ as the set $G$ arising from $G$ by omitting the condition about passing the zero-level, and define $\Theta(t, x)g$ by $g(t + \cdot) - x$. For details we refer to Miyazawa et al. (1998).

The right-continuous inverse function $\Lambda'(\cdot, \omega)$ is defined by

$$
\Lambda'(x, \omega) = \sup\{s \in \mathbb{R} : \Lambda(s, \omega) \leq x\}, \quad x \in \mathbb{R}.
$$

Hence, $\Lambda'$ is another RTC. From the two-dimensional family $\Theta$ we define two one-dimensional groups, $\{\theta_t : t \in \mathbb{R}\}$ and $\{\eta_x : x \in \mathbb{R}\}$, of transformations by

$$
\theta_t\omega := \Theta(t, \Lambda(t, \omega))\omega \text{ and } \eta_x\omega = \Theta(\Lambda'(x, \omega), x)\omega, \quad \omega \in \Omega \text{ and } t, x \in \mathbb{R}.
$$

It follows immediately that, for all $\omega \in \Omega$ and $t, s, x, y \in \mathbb{R}$,

$$
\begin{align*}
\Lambda(t) \circ \theta_s &= \Lambda(t + s) - \Lambda(s), \\
\Lambda'(y) \circ \eta_x &= \Lambda'(y + x) - \Lambda'(x), \\
\Lambda'(x) \circ \theta_t &= \Lambda'(x + \Lambda(t)) - t, \\
\Lambda(t) \circ \eta_x &= \Lambda(t + \Lambda'(x)) - x, \\
\eta_x \circ \theta_t &= \eta_{x+\Lambda(t)} \text{ and } \theta_t \circ \eta_x = \theta_{t+\Lambda'(x)}.
\end{align*}
\tag{2.1}
$$
The transformations $\theta_t$ and $\eta_x$ will be called shifts. By Lemma 2.3 of the above reference, the two invariant $\sigma$-fields of the $\theta$-shifts and the $\eta$-shifts coincide. We denote this $\sigma$-field by $\mathcal{I}$ and note that $\mathcal{I}$-measurable functions on $\Omega$ are invariant under all shifts of both types.

We next introduce a probability measure $P$ on $(\Omega, \mathcal{F})$. We will always assume that under $P$, the $\theta$-group is stationary and the long-run average $\bar{\Lambda} := \lim_{t \to \infty} \Lambda(t)/t$ is positive and finite. I.e.,

(ii) $P(\theta_t^{-1} A) = P(A)$ for all $t \in \mathbb{R}$ and $A \in \mathcal{F}$,

(iii) $P(0 < \bar{\Lambda} < \infty) = 1$.

So, we assume that the RTC $\Lambda$ satisfies (i)-(iii). These assumptions are sufficient to consider the probability measure $P_{\Lambda}$, the detailed Palm distribution (DPD) of $P$ w.r.t. $\Lambda$. It is defined by

$$P_{\Lambda}(A) = E \left( \frac{1}{\Lambda} \int_0^{\Lambda(1)} 1_A \circ \eta_x \, dx \right), \quad A \in \mathcal{F}. \tag{2.2}$$

In Miyazawa et al. (1998) it is proved that all shifts $\eta_y, y \in \mathbb{R}$, are measure preserving under $P_{\Lambda}$. So, the $\eta$-group is stationary under $P_{\Lambda}$. It is also proved that the following inversion formula holds:

$$P(A) = E_{\Lambda} \left( \frac{1}{\bar{\Lambda}} \int_0^{\Lambda'(1)} 1_A \circ \theta_s ds \right), \quad A \in \mathcal{F}, \tag{2.3}$$

and that $P_{\Lambda}$ and $P$ are dual in the sense that the DPD of $P_{\Lambda}$ w.r.t $\Lambda'$ gives $P$ in return. Here $\bar{N} := \lim_{t \to \infty} \Lambda'(t)/t = 1/\bar{\Lambda}$, and $E_{\Lambda}$ denotes expectation under $P_{\Lambda}$. Another distribution of Palm type is also considered, the well-known (ordinary) Palm distribution $P^0$ (shortly OPD) of $P$ w.r.t. $\Lambda$. It is defined below with the right-hand form as the most known:

$$P^0(A) = E \left( \frac{1}{\Lambda} \int_0^{\Lambda(1)} 1_A \circ \theta_{\Lambda''}(x) dx \right) = E \left( \frac{1}{\bar{\Lambda}} \int_{(0,1]} 1_A \circ \theta_t \Lambda(dt) \right), \quad A \in \mathcal{F}. \tag{2.4}$$

The relationship between $P, P_{\Lambda}$, and $P^0$ is further expressed in the following formulas. Here $E^0$ denotes expectation under $P^0$, and $\Lambda\{0\} := \Lambda(0) - \Lambda(0^-)$ is the jump-size at 0. The expressions in (2.6) hold both $P$- and $P_{\Lambda}$-a.s.
\[ P^0(A) = P_\Lambda(\theta_0^{-1}A) \quad \text{and} \quad P_\Lambda(A) = E^0 \left( \frac{1}{A\{0\}} \int_{-A\{0\}}^{0} 1_A \circ \eta_x \, dx \right), \quad (2.5) \]

\[
\lim_{t \to \infty} \frac{1}{t} \int_{0}^{t} 1_A \circ \theta_x \, ds = P(A|\mathcal{I}) \quad \text{and} \quad \lim_{y \to \infty} \frac{1}{y} \int_{0}^{y} 1_A \circ \eta_x \, dx = P_\Lambda(A|\mathcal{I}), \quad (2.6) 
\]

\[
\lim_{y \to \infty} \frac{1}{y} \int_{0}^{y} P \left( \eta_x^{-1} A \right) \, dx = P_\Lambda(A) \quad \text{and} \quad \lim_{y \to \infty} \frac{1}{y} \int_{0}^{y} P \left( \theta_{\Lambda^{-1}(x)} A \right) \, dx = P^0(A), \quad (2.7)
\]

\[
\lim_{t \to \infty} \frac{1}{t} \int_{0}^{t} P_\Lambda \left( \theta_s^{-1} A \right) \, ds = P(A); \quad A \in \mathcal{F}. \quad (2.8)
\]

These relations have very natural and intuitive meanings in the canonical case. For instance, the left-hand part of (2.7) indicates that starting with \( P \) we can obtain \( P_\Lambda \) by randomly choosing a level \( x \) on the positive half-line and shifting the origin to the position on the extended graph which corresponds to this level. The OPD can be obtained by shifting (if necessary) this randomly chosen level \( x \) up to the position on the graph. For more details we again refer to Miyazawa et al. (1998). In this reference it is also proved that every random measure \( \Lambda^* \) which satisfies the usual assumptions in random measure theory, can be characterized by a suitably chosen RTC \( \Lambda \) satisfying (i)-(iii). Hence, this RTC setting includes the random measure framework.

Since so many distributions are involved, we will sometimes attach the distribution to describe a property. For instance, we will talk about \( P \)-independency if independency under \( P \) is meant. \( P_\Lambda \)-distributed means distributed under \( P_\Lambda \).

If \( \Lambda \) is continuous and strictly increasing (with probability one), then \( \Lambda \) nor \( \Lambda' \) makes jumps. This case will be shortly considered now, under the assumption that, with probability one, \( \Lambda \) is almost everywhere differentiable. At first, note that \( P_\Lambda \) and \( P^0 \) coincide because of continuity. Writing \( \lambda(\cdot, \omega) \) for the derivative of \( \Lambda(\cdot, \omega) \) it follows immediately from the assumptions that, at least \( P \)-a.s.,

\[ \lambda(t, \omega) = \lambda(0, \theta_t \omega) \quad \text{for almost all} \ t \in \mathbb{R}. \]

By the right-hand side of (2.4) we obtain that
\[ P_\lambda(A) = P^0(A) = E \left( \frac{\lambda(0)}{\Lambda} 1_A \right), \quad A \in \mathcal{F}. \]

So, \( P_\lambda \) arises from \( P \) by changing the importance of the realizations by way of the weight function \( \lambda(0)/\Lambda \). That is, \( P_\lambda \) describes a change of measure.

The case that \( \Lambda \) makes jumps is more complicated. For the larger part of the present research we will assume that \( \Lambda \) makes jumps, i.e. that

\[(iv) \quad p := P_\lambda(\Lambda \{0\} > 0) \text{ is positive.}\]

The case that \( \Lambda \) is continuous (that is, \( p = 0 \)) while its graph has horizontal parts, implies that \( \Lambda' \) makes jumps. This case can easily be treated by using the duality property mentioned above and will be considered shortly in Section 3.

Assume that (iv) is satisfied. Let \( T_i, i \in \mathbb{Z}, \) be the (random) jump times at which the RTC jumps, under the convention that \( \cdots < T_{-1} < T_0 \leq 0 < T_1 < T_2 < \cdots \). Furthermore, set \( D_i := \Lambda(T_{i-}) \) and \( S_i := \Lambda(T_i), \quad i \in \mathbb{Z} \). If \( q := 1 - p = P_\lambda(\Lambda \{0\} = 0) \) is also positive, then there are - under \( P_\lambda \) - two typical types of realizations. The important point here is the position of the origin: it falls in a jump-part of the extended graph, or in a continuous part. Set

\[ P_{1\Lambda} := P_\lambda(\{\Lambda \{0\} > 0 \}) \quad \text{and} \quad P_{2\Lambda} := P_\lambda(\{\Lambda \{0\} = 0 \}). \]

The two types of realizations are just versions of the RTC under \( P_{1\Lambda} \) and \( P_{2\Lambda} \), respectively. Note that

\[ P_\lambda = pP_{1\Lambda} + qP_{2\Lambda}. \quad (2.9) \]

Note that it is not forbidden that \( D_i - S_{i-1} \) equals zero, i.e. that \( \Lambda \) does not increase on \( (T_{i-1}, T_i) \). We want to identify the non-empty intervals \( (S_{i-}, D_i) \) on the vertical axis. For \( i \in \mathbb{Z} \), let \( K(i) \) be the index of the \( i \)th jump-time in order for which \( D_{K(i)} = S_{K(i)} \) is strictly positive, with the convention that \( K(1) = 1 \) and \( K(0) \leq 0 \). Set \( T_i^* := T_{K(i)}, S_i^* := \Lambda(T_i^*) \) and \( D_{i+1}^* := \Lambda(T_{K(i)+1}^*) \). Note that \( D_{i+1}^* \) is not necessarily equal to \( \Lambda(T_{i+1}^*) \), and that \( D_{i+1}^* - S_i^* > 0 \). Furthermore, set

\[ U := \frac{T_1}{T_1 - T_0}, \quad U^* := \frac{T_i^*}{T_i^* - T_0^*}, \quad U' := \frac{S_0}{S_0 - D_0} \quad \text{and} \quad U'' := \frac{D_i^*}{D_i^* - S_0^*}. \]
(The definitions of $U^*$ and $U''$ require that $q > 0$.) Note that $U'' = D_1/(D_1 - S_0)$ \( P_{2A} \)-a.s. since $P_\Lambda(\Lambda(t) > 0 \text{ for all } t > 0) = 1$ by (2.2).

**Lemma 2.1.** Assume that $\Lambda$ satisfies (i)-(iv). Then

(a) For all $t \in \mathbb{R}$ it holds that $\theta_t^{-1} \mathcal{F}$ and $U'$ are independent under $P_{1\Lambda}$, while $U'$ is uniform (0,1) distributed.

(b) For all $n \in \mathbb{Z}$ it holds that $\theta_{T_n}^{-1} \mathcal{F}$ and $U$ are independent under $P$, while $U$ is uniform (0,1) distributed.

(c) Let $q > 0$. For all $n \in \mathbb{Z}$ it holds that $\theta_{T_n}^{-1} \mathcal{F}$ and $U^*$ are independent under $P$, while $U^*$ is uniform (0,1) distributed.

(d) Let $q > 0$. For all $n \in \mathbb{Z}$ it holds that $\theta_{T_n}^{-1} \mathcal{F}$ and $U''$ are independent under $P_{2A}$, while $U''$ is uniform (0,1) distributed.

**Proof.** Let $f$ and $g$ be suitably measurable functions. Denote the number of $S_i$'s in $(0, y]$ by $M(y)$. By (2.7) and (2.1) we have, since $\Lambda'(x) = T_i$ for all $x \in (D_i, S_i)$,

$$E_{1\Lambda}(f(U')g \circ \theta_t) = \frac{1}{p} \lim_{y \to \infty} E \left( \frac{1}{y} \int_0^y f(U'' \circ \eta_z) \cdot g \circ \theta_t \circ \eta_z \cdot 1_{(\Lambda(t) > 0) \cap \eta_z} \, dx \right)$$

$$= \frac{1}{p} \lim_{y \to \infty} E \left( \frac{1}{y} \sum_{i=1}^{M(y)} \int_{D_i}^{S_i} f \left( \frac{S_i - x}{S_i - D_i} \right) \, dx \cdot g \circ \theta_{i+T_i} \right)$$

$$= \frac{1}{p} \int_0^1 f(x) \, dx \cdot \lim_{y \to \infty} E \left( \frac{1}{y} \sum_{i=1}^{M(y)} (g \circ \theta_{i+T_i}(S_i - D_i)) \right).$$

Applying the above for $f \equiv 1$, yields for general $f$ and $g$:

$$E_{1\Lambda}(f(U')g \circ \theta_t) = \int_0^1 f(x) \, dx \cdot E_{1\Lambda}(g \circ \theta_t).$$

Part (a) follows. Parts (b) and (c) can be proved in a similar way by using (2.8) and splitting $(0, t]$ into the parts $(T_{i-1}, T_i]$ and $(T_{i-1}, T_i^*)$, respectively. For (d) we use (2.7) again and split $(0, y]$ into the intervals $(S_{i-1}, D_i]$; note that $U'' = D_1/(D_1 - S_0)$ under $P_{2A}$.

\[\square\]
We need more definitions. Set

$$
\gamma_{i-1} := \frac{T_i - T_{i-1}}{S_{i-1} - D_{i-1}} \Lambda \quad \text{and} \quad \delta_{i-1} := \frac{T_i^* - T_{i-1}^*}{D_i^* - S_{i-1}^*} \Lambda, \quad i \in \mathbb{Z},
$$

$$
X := U\gamma_0 = \frac{T_1}{S_0 - D_0} \Lambda \quad \text{and} \quad Y := U^*\delta_0 = \frac{T_1^*}{D_1^* - S_0^*} \Lambda,
$$

(2.10) (2.11)

provided that these random variables are well-defined. (For instance, the definition of \( \delta_{i-1} \) requires that both \( p \) and \( q \) are positive.)

**Lemma 2.2.** Assume that \( A \) satisfies (i)-(iv). Then:

(a) \( U \) and \( \gamma_0 \) are \( P \)-independent. If \( q > 0 \), then \( U^* \) and \( \delta_0 \) are \( P \)-independent.

(b) \( U^* \) and \( \gamma_0 \) are \( P_{1A} \)-independent.

(c) If \( q > 0 \), then \( U'' \) and \( \delta_0 \) are \( P_{2A} \)-independent.

(d) The conditional \( P \)-distribution of \( X \) given \( \gamma_0 \) is uniform \((0, \gamma_0)\).

(e) If \( q > 0 \), then the conditional \( P \)-distribution of \( Y \) given \( \delta_0 \) is uniform \((0, \delta_0)\).

**Proof.** Since \( \gamma_0 = \gamma_0 \circ \theta_{T_0} \), \( \delta_0 = \delta_0 \circ \theta_{T_0}^* \), and \( \gamma_0 = \gamma_0 \circ \theta_{T_0}^* \), the parts (a), (b) and (c) follow immediately from Lemma 2.1. For nonnegative \( a \) and \( b \) we obtain, by conditioning on \( \gamma_0 \), that

$$
P (\gamma_0 \leq a \text{ and } X \leq b) = E \left( 1_{(\gamma_0 \leq a)} \left( 1 \wedge \frac{b}{\gamma_0} \right) \right),
$$

cf. (2.11) and (a). A similar result holds for \( \delta_0 \) and \( Y \). Parts (d) and (e) follow immediately. \( \square \)

We end this section with a well-known, general result. Let \( Q_1, Q_2 \) and \( Q \) be probability measures on a common measurable space. Suppose that the null-sets of \( Q \) are also null-sets of both \( Q_1 \) and \( Q_2 \). Let \( h_i \) be the density of \( Q_i \) w.r.t. \( Q \) \((i = 1, 2)\). Then

$$
2 \sup_A |Q_1(A) - Q_2(A)| = \int |h_1 - h_2| dQ.
$$

(2.12)

(See, e.g., Nieuwenhuis (1998) for a short proof.)
3 Two-step procedures

At first sight there seem to be large gaps between the distribution $P$ on one hand and the distributions of Palm type on the other hand. However, the gaps can be bridged by simple two-step procedures, all consisting of a change of measure followed by a shift operation (or vice versa). For the simple PP case, it is well-known that the time-stationary distribution $P$ can be transformed into the PD by a two-step procedure. First the origin is shifted to the last arrival on its left, then the importance of the realizations is changed by a change of measure. In this section we will study similar bridging procedures for the general RTC case.

In view of Lemma 2.1 we can, in a sense, consider

$$
\sigma := D_0 + U(S_0 - D_0) \quad \text{and} \quad \tau := S_0^* + U^*(D_1^* - S_0^*)
$$

(3.1)

as arbitrarily chosen positions in the intervals $(D_0, S_0)$ and $(S_0^*, D_1^*)$, respectively. With this observation in mind the following theorem is intuitively obvious.

**Theorem 3.1.** Let $\Lambda$ be an RTC which satisfies (i)-(iii).

(a) If $p > 0$, then $P(\eta_0^{-1} A) = p E_{1A}(\gamma_0 1_A), \ A \in \mathcal{F}$.

(b) If $p, q > 0$, then $P(\eta_0^{-1} A) = q E_{2A}(\delta_0 1_A), \ A \in \mathcal{F}$.

**Proof.** (a). The proof is mainly based on (2.6) and (2.8). Let the number of jump times in the interval $(0, t]$ be denoted by $N(t)$. Since

$$
\eta_0 \circ \theta_0 = \eta_L(s) \quad \text{with} \quad L(s) := D_{i-1} + \frac{T_i - s}{T_i - T_{i-1}} (S_{i-1} - D_{i-1})
$$

for all $\omega \in \Omega$ and $s$ between $T_{i-1}(\omega)$ and $T_i(\omega)$, we obtain (by splitting the integral and changing the variable of integration):

$$
P(\eta_0^{-1} A) = \lim_{t \to \infty} E_A \left( \frac{1}{t} \sum_{i=1}^{N(t)} \int_{T_{i-1}}^{T_i} 1_A \circ \eta_0 \circ \theta_0 ds \right)
$$

$$
= \lim_{t \to \infty} E_A \left( \frac{1}{t} \sum_{i=1}^{N(t)} \int_{D_{i-1}}^{S_{i-1}} 1_A \circ \eta_x \cdot \frac{T_i - T_{i-1}}{S_{i-1} - D_{i-1}} dx \right)
$$

$$
= \lim_{t \to \infty} E_A \left( \frac{1}{t} \frac{A(t)}{A_1} \int_0^{A(t)} 1_A \circ \eta_x \cdot \frac{(T_i - T_0) \eta_x}{(S_0 - D_0) \eta_x} \cdot 1_{(\Lambda(0) > 0)} \eta_x dx \right)
$$

$$
= E_A \left( A E_A \left( 1_A \cdot \frac{T_i - T_0}{S_0 - D_0} \cdot 1_{(\Lambda(0) > 0)} | \mathcal{Z} \right) \right) = p E_{1A}(\gamma_0 1_A).
$$
The proof of (b) is similar. Let $N^*(t)$ be the number of $T_i^*$'s in $(0, t]$.

$$P(\eta_{\tau}^{-1}A) = \lim_{t \to \infty} E_A \left( \frac{1}{t} \sum_{i=1}^{N^*(t)} \int_{T_{i-1}^*}^{T_i^*} 1_A \circ \eta_{\tau} \circ \theta_{\tau} ds \right)$$

$$= \lim_{t \to \infty} E_A \left( \frac{1}{t} \sum_{i=1}^{N^*(t)} \left( \int_{S_{i-1}^*}^{S_i^*} 1_A \circ \eta_{\tau} dx \cdot \frac{T_i^* - T_{i-1}^*}{D_i^* - D_{i-1}^*} \right) \right)$$

$$= \lim_{t \to \infty} E_A \left( \frac{\Lambda(t)}{t} \int_0^{\Lambda(t)} 1_A \circ \eta_{\tau} \cdot \frac{(T_i^* - T_{i-1}^*)_{>0}}{(D_i^* - D_{i-1}^*)_{>0}} \cdot 1(\Lambda(0)=0) \circ \eta_{\tau} dx \right)$$

$$= E_A \left( \frac{\Lambda_\infty - \Lambda_0}{\Lambda(0) - \Lambda_0} 1(\Lambda(0)=0) \right) = q E_2(\delta_{01A}). \quad \square$$

As a consequence of part (a), the distributions $P_{1A}$ and $P_{\eta_{\tau}^{-1}}$ have the same null sets: if a statement holds $P_{1A}$-a.s. then it holds $P_{\eta_{\tau}^{-1}}$-a.s., and vice versa. The transformation of $P_{1A}$ into $P_{\eta_{\tau}^{-1}}$ as expressed in part (a) is nothing but a change of measure. In order to arrange this, the weight function $\rho_{\gamma_0}$, i.e. the Radon-Nikodym density of $P_{\eta_{\tau}^{-1}}$ w.r.t. $P_{1A}$, is used to change the importance of the realizations. Similar remarks can be made for part (b).

Since $\gamma_0$ and $\delta_0$ are invariant under the shifts $\eta_{\tau}$ and $\eta_{\sigma}$, we have

$$P_{1A}(A) = \frac{1}{p} E \left( \frac{1}{\gamma_0} 1_A \circ \eta_{\sigma} \right) \quad \text{and} \quad P_{2A}(A) = \frac{1}{q} E \left( \frac{1}{\delta_0} 1_A \circ \eta_{\tau} \right), \quad (3.2)$$

$$P_A(A) = E \left( \frac{1}{\gamma_0} 1_A \circ \eta_{\sigma} \right) + E \left( \frac{1}{\delta_0} 1_A \circ \eta_{\tau} \right), \quad A \in \mathcal{F}, \quad (3.3)$$

if $p$ and $q$ are positive. Consequently,

$$E \left( \frac{1}{\gamma_0} \right) = p = \frac{1}{E_{1A}(\gamma_0)} \quad \text{and} \quad E \left( \frac{1}{\delta_0} \right) = q = \frac{1}{E_{2A}(\delta_0)}.$$

The fractions of the increase of the random function $\Lambda$ caused by jumps and continuous parts are just the fractions $p$ and $q$, respectively.

Recall the definitions of $U'$ and $U''$ below (2.9). Set $V := T_0 + U'(T_1 - T_0)$ and $W := T_0^* + U''(T_1^* - T_0^*)$. In a sense $\eta_{\sigma}$ and $\theta_V$ (and also $\eta_{\tau}$ and $\theta_W$) are inverse transformations. This is expressed in the following relations.

$$\theta_V \circ \eta_{\sigma} = \theta_0, \quad \text{and} \quad \eta_{\sigma} \circ \theta_V = \eta_0 \quad P_{1A}\text{-a.s.;} \quad (3.4)$$
\[ \theta_W \circ \eta_r = \theta_0, \quad \text{and} \quad \eta_r \circ \theta_W = \eta_0 \quad \text{P}_{2\Lambda} \text{-a.s.}; \]  
\[ \eta_\sigma \circ \theta_W = \eta D_0 - (S_0 / (D_1 - S_0)) (S_0 - D_0) \quad \text{if} \quad T_0^* = T_0 \quad \text{and} \quad T_1^* = T_1; \]  
\[ \eta_r \circ \theta_V = \eta S_0 - (D_0 / (S_0 - D_0)) (D_1 - S_0) \quad \text{if} \quad T_0^* = T_0 \quad \text{and} \quad T_1^* = T_1. \]  

As a consequence of Theorem 3.1, (3.4) and (3.5) we obtain, for all \( A \in \mathcal{F} \),
\[ P(A) = p E_{1A} (\gamma_0 1_A \circ \eta_V) \quad \text{if} \quad p > 0, \]  
\[ P(A) = q E_{2A} (\delta_0 1_A \circ \theta_W) \quad \text{if} \quad p, q > 0. \]  

Theorem 3.1 and Relations (3.2), (3.8) and (3.9) can be summarized in the following diagrams, where \( \sim \) means that the corresponding probability measures have the same null-sets.
\[ P \sim P_{1\Lambda} \theta_V^{-1} \quad P \sim P_{2\Lambda} \theta_W^{-1} \]
\[ \eta_\sigma \downarrow \quad \downarrow \eta_\sigma \quad \eta_r \downarrow \quad \downarrow \eta_r \quad P \eta_\sigma^{-1} \sim P_{1\Lambda} \quad P \eta_r^{-1} \sim P_{2\Lambda} \]  

The left-hand diagram expresses that the Radon-Nikodym density of \( P \) w.r.t. \( P_{1\Lambda} \theta_V^{-1} \), i.e. \( p \gamma_0 \), is not affected by applying the shift \( \eta_\sigma \) (cf. Th. 3.1(a) and (3.8)). Transformation of \( P \) into \( P_{1\Lambda} \) (or vice versa) can be arranged by either of two two-step procedures. The first procedure goes clockwise, with the first step being a change of measure and the second the application of the shift \( \eta_\sigma \) (or \( \theta_V \)). The second two-step procedure works counter-clockwise with the steps in reversed order. For the right-hand diagram similar observations hold. See also p. 47 of Nieuwenhuis (1994) for the PD in the simple point process case, and Sections 4 and 5 in Thorisson (1995).

For completeness, we note that the above results can (if \( p, q > 0 \)) also be used to transform \( P_{2\Lambda} \) into \( P_{1\Lambda} \) or vice versa. Application of (3.2) and (3.9), and (3.2) and (3.8) respectively yield:
\[ P_{1\Lambda} (A) = \frac{q}{p} E_{2A} \left( \frac{\delta_0}{\gamma_0 \circ \theta_W} 1_A \circ \eta_\sigma \circ \theta_W \right), \]  

(3.11)
\[ P_{2A}(A) = \frac{p}{q} E_{1A} \left( \frac{\gamma_0}{\theta_0} 1_A \circ \eta \circ \theta_V \right); \quad A \in \mathcal{F}. \quad (3.12) \]

See also (3.6) and (3.7).

We next investigate the consequences for \( P^0 \), the OPD of \( A \). Set \( P_1^0 := P^0(\mid A \mid \{0\} > 0) \) and \( P_2^0 = P^0(\mid A \mid \{0\} = 0) \). By (2.5) it follows immediately that

\[ P^0 = pP_1^0 + qP_2^0, \quad P_1^0 = P_1A \theta_0^{-1} \text{ and } P_2^0 = P_2A. \quad (3.13) \]

Consequently, the above right-hand diagram can also be used for \( P_2^0 \). For \( P_1^0 \) it follows from (3.13), (3.2), (3.8) and (2.5) that

\[ P_1^0(A) = \frac{1}{p} E \left( \frac{1}{\gamma_0} 1_A \circ \theta_{T_0} \right) \quad \text{and} \quad P(A) = pE_1^0 \left( \frac{X}{\Lambda \{0\}} \int_0^{T_1} 1_A \circ \theta_s ds \right), \quad (3.14) \]

where \( A \in \mathcal{F} \). Here \( E_1^0 \) denotes expectation under \( P_1^0 \). With \( P' \) defined by

\[ P'(A) := \frac{1}{p} E \left( \frac{1}{\gamma_0} 1_A \right), \quad A \in \mathcal{F}, \quad (3.15) \]

we obtain the following diagram:

\[ P \sim P' \]

\[ \theta_{T_0} \downarrow \quad \downarrow \theta_{T_0} \]

\[ P \theta_{T_0}^{-1} \sim P_1^0 \]

Similar to the diagrams in (3.10), this diagram gives two two-step procedures to generate \( P_1^0 \) from \( P \), clockwise or counter-clockwise. In fact this is the immediate generalization of the diagram in Nieuwenhuis (1994) if OPD's are concerned. See also Thorisson (1995).

**Example 3.1.** Let \( \Lambda = \Phi \) be a, not necessarily simple, point process (i.e., an RTC with \( p = 1 \) and integer-valued jump-sizes) which satisfies (i)-(iii). The relationships between \( P \), the DPD, and the OPD follow immediately from the above theory. However, in Miyazawa et al. (1998) it was noted that the following distribution is of more interest:

\[ \overline{P}_\Phi := P_\Phi \eta_\alpha^{-1}, \quad (3.16) \]
with \( \alpha := \max\{\Phi(0) - i : i \in \mathbb{N}_0 \text{ and } \Phi(0) - i \leq 0 \} \) the largest non-positive number which is integer-distanced from \( \Phi(0) \). The distribution \( \overline{P}_\Phi \) has nice stationarity properties, can "distinguish between simultaneous arrivals within a batch of arrivals", and is (for the present time change set-up) the equivalence of a similar distribution in Brandt et al (1990). It follows immediately that \( P_0 \circ \theta_0^{-1} = \overline{P}_\Phi \circ \theta_0^{-1} \). From this result, (3.2) and (3.14) we obtain immediately that

\[
\overline{P}_\Phi(A) = E\left( \Phi(T_0) \right) - \Phi(T_0) \cdot 1_{A \circ \eta_\sigma} \quad \text{and} \quad P(A) = \overline{E}_\Phi \left( \Phi(0) \int_0^{T_1} 1_{A \circ \theta_s} \right) ds, \tag{3.17}
\]

where \( \sigma \) is the largest number in \([D_0, \sigma]\) which is integer-distanced from \( D_0 \). Especially the left-hand part is of interest. It ensures that the time-stationary distribution \( P \) can be transformed into the distribution \( \overline{P}_\Phi \) by a two-step procedure, consisting of a change of measure and the application of the shift \( \eta_\sigma \). These observations are not only of interest for getting a good understanding of \( \overline{P}_\Phi \), but also for simulation purposes. See Section 5.

For completeness, we end this section with shortly considering the case that \( p = 0 \), i.e. \( A \) is continuous, but \( A \) has constant parts. That is, \( p' := P(\Lambda'(\{0\} > 0) > 0 \) is positive. In Miyazawa et al (1998) it is noticed that \( P_A \) and \( P \) are dual in the sense that the DPD of \( P_A \) w.r.t. \( \Lambda' \) is equal to \( P \). From the arguments in Section 4 of this reference it follows immediately that the results in the present research remain valid if \( A \) is replaced by \( \Lambda' \), \( P \) by \( P_A \), \( P \) by \( \theta \), \( \eta \) by \( \eta_\sigma \) and \( \theta \) by \( \theta_\sigma \). In this context we also replace functions of \( A \) by functions of \( A' \), adding a prime in the notations. For instance, \( T'_i \) is the \( i \)-th occurrence of \( \Lambda' \), \( D'_i := \Lambda'(T'_i) \), \( S'_i := \Lambda'(T'_i) \), and \( \sigma' := D'_0 + T'_1(S'_0 - D'_0)/(T'_1 - T'_0) \). Set \( P_1(B) := P(B|A' \{0\} > 0) \). With these considerations in mind, we can (for instance) deduce from Theorem 3.1(a), (3.2) and (3.8) that

\[
P_A(\theta_{\sigma'}^{-1}A) = p' E_1(\gamma'_0 1_A),
\]

\[
P(A) = \frac{1}{p'} E_A \left( \frac{1}{\gamma'_0} 1_A \circ \theta_{\sigma'} \right),
\]

\[
P_\Lambda(A) = p' E_1(\gamma'_0 1_A \circ \eta_{\sigma'}); \quad A \in \mathcal{F}.
\]
4 Local characterization of PD’s

The PD of a point process with only single arrivals is often described as a conditional distribution, given an arrival in the origin. This intuitive interpretation of the PD is justified by the well-known local characterization theorem. In the present section we will consider local aspects of Palm theory for general RTC’s. At first we derive a result which specializes to Dobrushin’s lemma in case of an ergodic PP. Then we prove results which give local characterizations of the conditional DPD’s and OPD’s. In case of an arrival process with batches, this leads to a heuristic interpretation of $P_{\Phi}$ as a conditional distribution.

Let $F$ be the $P$-distribution function of

$$X - U - T_{1}/(S_{0} - D_{0})$$

(cf. (2.11)) and suppose that $\rho > 0$. By Lemma 2.2(d) and Theorem 3.1(a) we have for all $t \geq 0$:

$$F(t) = P(X \leq t) = E \left( \frac{t}{\gamma_{0}} \wedge 1 \right) = pE_{1A}(t \wedge \gamma_{0})$$

(4.1)

Hence, $F$ is differentiable with derivative $F'(t) = pE_{1A}(\gamma_{0} > t)$. Again by Theorem 3.1(a), we obtain:

$$F(t) = P(\gamma_{0} \leq t) + ptP_{1A}(\gamma_{0} > t), \quad t \geq 0.$$  

(4.2)

From this it follows immediately that $F(t) \geq ptP_{1A}(\gamma_{0} > t)$ and that

$$F(t) = pE_{1A}(\gamma_{0} \leq t) - ptP_{1A}(\gamma_{0} \leq t) + pt \leq 0 + pt.$$  

Consequently,

$$\lim_{t \downarrow 0} \frac{1}{t} F(t) = p \quad \text{if} \quad p > 0.$$  

(4.3)

If $\Lambda = \Phi$ is a simple, ergodic PP with intensity $\lambda$, then (4.3) can be rewritten as $P(\Phi(0, t]) > 0 = \lambda t + o(t)$, as $t \to 0$. This is just Dobrushin’s lemma; see, e.g., Baccelli and Brémaud (1994; p. 39).

If both $p$ and $q$ are positive, we can derive similar results for the $P$-distribution function $G$ of $Y$ (cf. (2.11)); just replace $p$ and $\gamma_{0}$ in (4.1)-(4.3) by $q$ and $\delta_{0}$. The same holds for the $P_{1A}$ and the $P_{2A}$ distribution functions $H$ and $J$ of
respectively. Just replace \((p, P_{1A}, \gamma_0, P)\) by \((1/p, P, 1/\gamma_0, P_{1A})\) and \((1/q, P, 1/\delta_0, P_{2A})\), respectively. (For the proofs, we use Lemma 2.2, parts (b) and (c).)

Recall that \(U = T_1/(T_1 - T_0)\) and \(X = T_1/\Lambda/(S_0 - D_0)\). For a simple and ergodic PP, local characterization expresses that \(P^0(A)\) can be approximated by the conditional probabilities \(P^0(P_{1A}|T_1 \leq 1/n, A)\), as \(n \to \infty\), leading to the well-known intuitive interpretation of \(P^0\) as a conditional distribution under \(P\). (See, e.g., Theorem 10 in Nieuwenhuis (1994) for a uniform version.) In view of this observation, one might expect that, in the general RTC case, the conditional probabilities \(P(\eta^{-1}_A|X \leq 1/n)\) tend to \(P_{1A}(A)\) as \(n \to \infty\). Note in this context that

\[(S_0 - D_0) \circ \eta = S_0 - D_0 \quad \text{and} \quad D_0 \circ \eta = -U(S_0 - D_0).\]

With \(U'_0 := -D_0/(S_0 - D_0) = 1 - U'\), we obtain by Theorem 3.1 and (4.1) that

\[
P \left( \eta^{-1}_A | X \leq \frac{1}{n} \right) = \frac{E \left( 1_A \circ \eta \cdot 1(\frac{U'_0}{\gamma_0} \leq \frac{1}{n}) \circ \eta \right)}{E(1 \wedge \frac{1}{\gamma_0})} = \frac{E_{1A} \left( 1_A \gamma_0 \cdot 1(\frac{U'_0}{\gamma_0} \leq \frac{1}{n}) \right)}{E_{1A}(\gamma_0 \wedge \frac{1}{n})}.
\]

The choice \(A = (U'_0 \leq 1/2)\) makes clear that in general (4.5) will not tend to \(P_{1A}(A)\).

Studying (4.5) in more detail yields that a reason might be that, in spite of Lemma 2.1(b), the random variable \(U\) in \(X = U\gamma_0\) is \(P\)-dependent of \(A\). Let \(\tilde{U}_1\) be another uniform \((0,1)\) random variable on \((\Omega, \mathcal{F}, P)\), but \(\tilde{U}_1\) is assumed to be \(P\)-independent of \(\eta^{-1}\mathcal{F}\).

(Here we assume that \(\Omega\) is rich enough to support such a variable.) By conditioning on the \(\sigma\)-field generated by \(\gamma_0\) we obtain that

\[
P \left( \eta^{-1}_A | \tilde{U}_1 \gamma_0 \leq \frac{1}{n} \right) = \frac{E(1_A \circ \eta \cdot (1 \wedge \frac{1}{n}))}{E(1 \wedge \frac{1}{\gamma_0})} =: P_n(A).
\]

A similar relation can be obtained in terms of \(\tau\) and \(\delta_0\). Suppose that \(\tilde{U}_2\) is a uniform \((0,1)\) random variable which is \(P\)-independent of \(\eta^{-1}\mathcal{F}\). Then we have:

\[
P \left( \eta^{-1}_A | \tilde{U}_2 \delta_0 \leq \frac{1}{n} \right) = \frac{E(1_A \circ \eta \cdot (1 \wedge \frac{1}{\delta_0}))}{E(1 \wedge \frac{1}{\delta_0})} =: Q_n(A).
\]
Theorem 4.1. Suppose that the RTC \( \Lambda \) satisfies (i)-(iii). Then

\[
\sup_{A \in \mathcal{F}} |P_n(A) - P_{1A}(A)| = 1 - \frac{F(F(\frac{1}{n})/p)}{F(\frac{1}{n})} \to 0,
\]

(4.8)

\[
\sup_{A \in \mathcal{F}} |Q_n(A) - P_{2A}(A)| = 1 - \frac{G(G(\frac{1}{n})/p)}{G(\frac{1}{n})} \to 0
\]

(4.9)

as \( n \to \infty \), provided that \( p \) is positive, and both \( p \) and \( q \) are positive, respectively.

Proof. Set \( h(n) = F(1/n)/p \). By Theorem 3.1 it follows immediately that the null-sets of \( P_{1A} \) are also null-sets of \( P_n \). By (2.12) the supremum in (4.8) is equal to \( E_{1A}|\gamma_0 \wedge (1/n) - h(n)|/(2h(n)) \). This in turn can be written as a summation of \( P_{1A} \) and \( P \)-probabilities by restricting to \( (\gamma_0 \leq h(n)), \ (h(n) < \gamma_0 \leq 1/n), \) and \( (\gamma_0 > 1/n), \) and applying Theorem 3.1(a). The equality in (4.8) follows by properly applying (4.2). The convergence in (4.8) is a consequence of (4.3): replace \( t \) by \( F(1/n)/p \). The proof of (4.9) is similar. \( \square \)

Remark 4.1. Note that \( P_n \) and \( Q_n \) do not depend on \( \tilde{U}_1 \) and \( \tilde{U}_2 \), respectively. Since \( 1_A \circ \theta_0 \circ \eta_0 = 1_A \circ \theta_{T_0} \) and since (cf. Lemma 2.1) \( U = T_1/(T_1 - T_0) \) is indeed \( P \)-independent of \( \theta_{T_0}^{1} \mathcal{F} \), it follows immediately that

\[
\sup_{A \in \mathcal{F}} |P \left( \theta_{T_0}^{-1}A | X \leq \frac{1}{n} \right) - P_{1A} \left( \theta_{T_0}^{-1}A \right)| \to 0
\]

(4.10)

as \( n \to \infty \). Since \( P_{1A} \theta_{T_0}^{-1} \) is just the conditional OPD (cf. (3.13)), result (4.10) is for the present RTC-setting the generalization of Theorem 10 in Nieuwenhuis (1994). See also Thorisson (1995) for a process with cycles setting. If \( p = 1 \) (i.e., if \( \Lambda \) is a pure jump process), then (4.10) expresses local characterization of the OPD of \( \Lambda \). It is well-known in the case of simple PP's. \( \square \)

Unfortunately, we had to choose an abstract uniform \((0,1)\) random variable \( \tilde{U}_1 \) - that is, not a concrete function of \( \Lambda \) - to arrange the desired independence and the local characterization in (4.8); recall the arguments between (4.5) and (4.6). As a corollary, (4.8) does, for a general RTC, not lead to a nice heuristical interpretation of \( P_{1A} \). However, in special cases \( \tilde{U}_1 \) can be shaped. We investigate local characterization of \( P_\phi \), the
suitable distribution of detailed Palm type in case the RTC is a not necessarily simple point process $\Phi$; see Example 3.1. As usual, we assume that within a batch the arrivals are ordered. Although $\overline{P}_\Phi = P_\Phi \eta_\alpha^{-1}$, we can't use an approach as in Remark 4.1 since $\eta_\alpha \circ \eta_\alpha = \eta_{[\cdot]}$ depends on $U$, and $U$ and $\eta_{[\cdot]}^{-1} \mathcal{F}$ are $P$-dependent. It seems that we really need an abstract uniform $(0,1)$ random variable as $\tilde{U}$ in (4.6). However, in the present PP case we still can choose $\tilde{U}$ as a function of $\Phi$. Recall that $T_{i-1}$ is the $(i-1)$th jump-time, and that $S_{i-1} - D_{i-1}$ is the corresponding jump-size (which is now integer-valued), $i \in \mathbb{Z}$. We divide the interval $[T_{i-1}, T_i]$ into $S_{i-1} - D_{i-1}$ subintervals of equal lengths by defining the intermediate times

$$
T_{i-1,j} := T_{i-1} + j \frac{T_i - T_{i-1}}{S_{i-1} - D_{i-1}}; \quad j = 0, \ldots, S_{i-1} - D_{i-1}. \tag{4.11}
$$

For $s$ between $T_{i-1,j-1}$ and $T_{i-1,j}$ we have:

$$
\eta_\alpha \circ \eta_\alpha \circ \theta_s = \eta_{S_{i-1}-j}; \quad j = 1, \ldots, S_{i-1} - D_{i-1}. \tag{4.12}
$$

Let $\hat{T}_0$ and $\hat{T}_1$ respectively be the smallest positive and the largest non-positive intermediate times in $[T_0, T_1]$, and set $\hat{U} := \hat{T}_1 / (\hat{T}_1 - \hat{T}_0)$. Note that $\hat{U} = \hat{T}_1(S_0 - D_0) / (T_1 - T_0)$ and that $\hat{U}^{-1} = \hat{T}_1 \Phi$. Part (b) below expresses local characterization of $\overline{P}_\Phi$.

**Theorem 4.2.** Let $\Phi$ be a PP which satisfies Assumptions (i)-(iii). Then:

(a) $\eta_{[\cdot]}^{-1} \mathcal{F}$ and $\hat{U}$ are independent under $P$, while $\hat{U}$ is uniform $(0,1)$ distributed.

(b) $\sup_{A \in \mathcal{F}} \left| P \left( \eta_{[\cdot]}^{-1} A \left| \frac{\hat{T}_1 \Phi}{n} \leq \frac{1}{n} \right. \right) - \overline{P}_\Phi(A) \right| \to 0.$

**Proof.**

(a) Let $f$ and $g$ be suitably measurable functions. Denote the number of $T_i$'s in $(0, t]$ by $N(t)$. By (2.8), and by splitting $(0, t]$ into the parts $(T_{i-1}, T_i]$ and splitting these intervals in turn into the sub-intervals constituted by the intermediate times, we obtain that
$$E(f(\hat{U})g \circ \eta_\sigma \circ \eta_{\sigma}) =$$
$$\lim_{t \to \infty} E_{\Phi} \left( \frac{1}{t} \sum_{l=1}^{N(t)} \sum_{j=1}^{T_{l-1,j}} f\left( \frac{T_{l-1,j} - s}{T_{l-1,j} - T_{l-1,j-1}} \right) \cdot g \circ \eta_{S_{l-1}-j} \right)$$
$$= \int_0^1 f(u) du \cdot \lim_{t \to \infty} E_{\Phi} \left( \frac{1}{t} \sum_{l=1}^{N(t)} \sum_{j=1}^{S_{l-1}-D_{l-1}} g \circ \eta_{S_{l-1}-j} \right)$$
$$= \int_0^1 f(u) du \cdot E(g \circ \eta_\sigma \circ \eta_{\sigma}).$$

Here the third equality follows for general $f$ and $g$, by applying the second equality for $f \equiv 1$.

(b) This follows from (4.6) and (4.8), replacing $A$ by $\eta^{-1}_\sigma A$, $\hat{U}_1$ by $\hat{U}$, and $\mathcal{F}$ by $\eta^{-1}_\sigma \mathcal{F}$. 

Remark 4.2. For a heuristic interpretation of part (b) of the theorem, recall that working under $P$ means that the origin is uniformly situated in the interval $(T_0, T_1)$; cf. (2.8) in the present research and Remark 4.1 in Miyazawa et al. (1998). Hence, letting $t$ tend to zero with $\bar{T}_1 \leq t$ implies that "in the end" the origin falls in an intermediate time, $M$ units of $(T_1 - T_0)/(S_0 - D_0)$ away from $T_1$. Here the integer-valued random variable $M$ is (conditionally) uniformly distributed on $\{1, \ldots, S_0 - D_0\}$. But in this ultimate situation, $\sigma$ equals $D_0 + M$. Hence, heuristically, $P_{\Phi}$ arises from $P$ by conditioning on the origin falling in an intermediate time, and - with $m$ intermediate times on its right in $(0, T_1]$-moving the origin to the $m$th arrival in order within the last batch of arrivals on its left.

Obviously, transitions from $P$ to $P_{1\sigma}$ and to $P_{2\sigma}$ (as described above) are important for getting a good understanding of the DPD of an RTC. For completeness, we shortly consider transitions the other way round: from $P_{1\sigma}$ to $P$ and from $P_{2\sigma}$ to $P$. Since $\theta_V$ and $\theta_W$ are in a sense the inverse shifts of $\eta_\sigma$ and $\eta_T$ respectively (see (3.4) and (3.5)), the following results are obvious:

$$P_{1\sigma}\left( \theta_V^{-1} A \mid \frac{\hat{U}_3}{\gamma_0} \leq \frac{1}{n} \right) = \frac{E_{1\sigma}(1_A \circ \theta_V \cdot \left( 1 \wedge \frac{\gamma_0}{n} \right))}{E_{1\sigma}\left( 1 \wedge \frac{\gamma_0}{n} \right)} =: R_n(A), \quad (4.13)$$
\[
P_{2n} \left( \theta_W^{-1} A \left| \frac{\hat{U}_4}{\hat{v}_0} \leq \frac{1}{n} \right. \right) = \frac{E_{2n}(1_A \circ \theta_W \cdot (1 \wedge \frac{\delta_0}{n}))}{E_{2n}(1 \wedge \frac{\delta_0}{n})} =: S_n(A),
\]

\( A \in \mathcal{F} \). Here \( \hat{U}_3 \) and \( \hat{U}_4 \) are uniform \((0,1)\) random variables, \( P_{1A} \)-independent of \( \theta_W^{-1} \mathcal{F} \) and \( P_{2A} \)-independent of \( \theta_V^{-1} \mathcal{F} \), respectively. By using the distribution functions \( H \) and \( J \) of \( Z_1 \) and \( Z_2 \) (see (4.4)), it can be proved that \( R_n(A) \) and \( S_n(A) \) tend to \( P(A) \), uniformly over \( A \in \mathcal{F} \).

## 5 Simulation applications

\( P \) describes the random behavior of the RTC as it is seen from a randomly chosen time-point (on the horizontal axis), \( P_\lambda \) as it is seen from a randomly chosen level (on the vertical axis). Under \( P \), a typical realization will have its origin in a continuous part of the graph, but it might be constant on a small interval \((0, \varepsilon)\). Under \( P_\lambda \), there are two types of typical realizations. For the first type the origin is in a jump-part, for the second it lies in a continuous part but the time change is strictly increasing on \((0, \varepsilon)\) for \( \varepsilon \) small enough. In the present section we will especially consider procedures for generating these two types of realizations when starting with realizations typical under \( P \). The procedures originate from Asmussen et al. (1992) and Thorisson (1995). In the case of a PP with multiple arrivals, the main procedure generates a version of the PP as seen through the eyes of an arbitrarily chosen arrival within a batch of simultaneous arrivals in the origin.

At first we generate a version of the RTC under \( P_{1A} \), starting with independent versions under \( P \). Let \( p \) be positive. For a version \( \Lambda_n \) of \( \Lambda \) we will occasionally write \( T_j^{(n)}, T_j^{(s(n)} \) (for \( j \in \mathbb{Z} \)), \( S_0^{(n)}, D_0^{(n)}, D_1^{(n)}, D_0^{*(n)}, D_1^{*(n), \gamma_0(n)}, \sigma_0(n), \sigma_n, \tau_n, V_n, \) and \( W_n \) in accordance with the corresponding definitions in Sections 2-4. For a positive and fixed constant \( b \), the recursive procedure (for \( n \in \mathbb{N} \)) with the steps

1. generate a version \( \Lambda_n \) of the RTC under \( P \), independent of \( \Lambda_1, \ldots, \Lambda_{n-1} \)

2. set \( \Lambda_{0n} := \Lambda_n \circ \eta_{\sigma_n} \)

3. generate under \( P \) a uniform \((0,1)\) observation \( U_n \), independent of \( U_1, \ldots, U_{n-1} \) and \( \Lambda_{01}, \ldots, \Lambda_{0n} \)

4. stop the procedure as soon as \( U_n \leq b/\gamma_0^{(n)} \) and set \( M := \min\{n \in \mathbb{N} : U_n \leq b/\gamma_0^{(n)}\} \),
leads to the version $\Lambda_{0M}$. For measurable functions $f$ we obtain that

$$E(f(\Lambda_{0M})) = \sum_{n=1}^{\infty} E(f(\Lambda_{0n})1_{(M=n)})$$

$$= \sum_{n=1}^{\infty} E(f(\Lambda_{0n})1_{(U_n \leq b/\gamma_0)}) P(M > n - 1)$$

$$= E(f(\Lambda_{01})1_{(U_1 \leq b/\gamma_0)}) \cdot E(M).$$

Note that

$$E(M) = \sum_{n=0}^{\infty} (P(U_1 > b/\gamma_0^{(1)})^n = 1/P(U_1 \leq b/\gamma_0^{(1)}),$$

$$E(f(\Lambda_{0M})) = \frac{E\left(f(\Lambda \circ \eta_{\sigma}) \cdot \left(1 \wedge \frac{b}{\gamma_0}\right)\right)}{E\left(1 \wedge \frac{b}{\gamma_0}\right)}$$

$$= \frac{E_{1A}(f(\Lambda)(\gamma_0 \wedge b))}{E_{1A}1(\gamma_0 \wedge b)}.$$  \hfill (5.1)

See Theorem 3.1(a) for the last equality; see also (4.6). By Theorem 4.1(a), the $P$-distribution of the version $\Lambda_{0M}$ of the RTC tends to the $P_{1A}$-distribution of the RTC as $b$ tends to zero from above. If $P(\gamma_0 > b) = 1$, it follows immediately that $E(f(\Lambda_{0M})) = E_{1A}(f(\Lambda))$. The following intuitive statement declares what is going on (renaming $\Lambda_{0M}$ as $\Lambda_{0M}^{(1)}$).

$$\Lambda_{0M}^{(1)}$$ is a typical version of the RTC as seen from a level chosen at random in its jump-parts, \hfill (5.2)

provided that $\gamma_0$ is bounded away from zero.

In the case that $\Lambda = \Phi$ is a PP with multiple arrivals, the above procedure can easily be adapted to generate a version of the PP as seen under $P_{\Phi}$. That is, to generate a version as seen through the eyes of an arbitrarily chosen arrival within a batch of simultaneous arrivals in the origin. Just replace step 2 by $\Lambda_{0n} := \Lambda_n \circ \eta_{\sigma_n} \circ \eta_{\sigma_n}$, replace all $\Lambda$'s by $\Phi$'s, and recall that in this case $P_{1A\eta_{\sigma}^{-1}}$ is just $P_{\Phi}$.

If both $p$ and $q$ are positive, a similar procedure leads to a typical version of the RTC as seen under $P_{2A}$: just replace $(\sigma_n, \gamma^{(n)}_0)$ by $(\tau_n, \xi^{(n)}_0)$. By Theorems 3.1(b) and 4.1(b),
we obtain that the \( P \)-distribution of the version \( \Lambda_{0M}^{(2)} \) which follows from the adapted procedure, tends to the \( P_{2A} \)-distribution of the RTC (as \( b \downarrow 0 \)), and

\[
\Lambda_{0M}^{(2)} \text{ is a typical version of the RTC as seen from a level chosen at random in its continuous parts, (5.3)}
\]

provided that \( \delta_0 \) is bounded away from zero.

With (3.8), (3.9), (4.13) and (4.14) in mind, we can also formulate procedures which work the other way round. Starting with versions \( \Lambda_n \) under \( P_{1A} \) or \( P_{2A} \), we just have to replace \((b, P, \eta_{\sigma_n}, \gamma_0^{(n)})\) in the procedure by \((1/b, P_{1A}, \theta_{V_n}, 1/\gamma_0^{(n)})\) or \((1/b, P_{2A}, \theta_{W_n}, 1/\delta_0^{(n)})\).

The respective versions \( \Lambda_{0M} \) are both versions of the RTC under \( P \).

For completeness we note that - under a similar boundedness condition - (3.11) (or (3.12)) leads to a procedure to derive an observation under \( P_{1A} \) (or \( P_{2A} \)), when starting with observations of the RTC under \( P_{2A} \) (or \( P_{1A} \)). Among more, we have to replace \( \eta_{\sigma_n} \) by \( \eta_{\sigma_n} \circ \theta_{W_n} \) (or \( \eta_{\tau_n} \circ \theta_{V_n} \)).
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