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Slightly $(\tau_1, \tau_2)p$-Continuous Multifunctions

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Abstract. Our main purpose is to introduce the concepts of upper and lower slightly $(\tau_1, \tau_2)p$-continuous multifunctions. Moreover, several characterizations of upper and lower slightly $(\tau_1, \tau_2)p$-continuous multifunctions are investigated.

1. Introduction

The concept of slightly continuous functions was introduced by Jain [35]. Nour [46] defined slightly semi-continuous functions as a weak form of slight continuity and investigated some characterizations of slightly semi-continuous functions. Noiri and Chae [45] have further investigated slightly semi-continuous functions. Pal and P. Bhattacharyya [47] introduced and studied the concept of faintly precontinuous functions. Slight continuity implies both slight semi-continuity and faint precontinuity. Duangphui et al. [32] introduced and investigated the notion of $(\mu, \mu')^{(m,n)}$-continuous functions. Dungthaisong et al. [33] introduced and studied the notion of $g_{(m,n)}$-continuous functions. Viriyapong and Boonpok [61] investigated some characterizations of (Λ, sp)-continuous functions by utilizing the notions of (Λ, sp)-open sets and (Λ, sp)-closed sets due to Boonpok and Khampakdee [19]. Moreover, some characterizations of almost (Λ, p)-continuous functions, strongly $\theta(\Lambda, p)$-continuous functions, almost strongly $\theta(\Lambda, p)$-continuous functions, $\theta(\Lambda, p)$-continuous functions, weakly (Λ, b)-continuous functions, $\theta(\star)$-precontinuous functions, $\star$-continuous functions, θ-$\mathscr{I}$-continuous functions, almost (g, m)-continuous functions, pairwise M-continuous functions, (τ_1, τ_2)-continuous functions, almost (τ_1, τ_2)-continuous functions, weakly (τ_1, τ_2)-continuous functions, almost quasi (τ_1, τ_2)-continuous functions and weakly

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quasi (τ_1, τ_2)-continuous functions were presented in [52], [54], [7], [49], [9], [10], [8], [23], [29], [28], [3], [4], [5], [40] and [31], respectively. Noiri [44] introduced the notion of slightly β-continuous functions and studied the relationships between slight β-continuity, contra-β-continuity [30] and β-continuity [1]. Sangviset et al. [51] introduced the concept of slightly (m, μ)-continuous functions as functions from an m-space into a generalized topological space and investigated some characterizations of slightly (m, μ)-continuous functions.

In 2005, Ekici [34] introduced and studied the concepts of upper and lower slightly α-continuous multifunctions as a generalization of upper and lower α-continuous multifunctions, respectively, due to Neubrunn [42]. Viriyapong and Boonpok [62] introduced and investigated the concept of $(\tau_1, \tau_2)\alpha$-continuous multifunctions. Laprom et al. [41] introduced and studied the notions of upper and lower $\beta(\tau_1, \tau_2)$-continuous multifunctions. Furthermore, some characterizations of $(\tau_1, \tau_2)\delta$-semicontinuous multifunctions, almost weakly (τ_1, τ_2)-continuous multifunctions, $\star$-continuous multifunctions, $\beta(\star)$-continuous multifunctions, weakly quasi (Λ, sp)-continuous multifunctions, α-$\star$-continuous multifunctions, almost α-$\star$-continuous multifunctions, almost quasi $\star$-continuous multifunctions, weakly α-$\star$-continuous multifunctions, $s\beta(\star)$-continuous multifunctions, weakly $s\beta(\star)$-continuous multifunctions, $\theta(\star)$-quasi continuous multifunctions, almost $\iota^\star$-continuous multifunctions, weakly (Λ, sp)-continuous multifunctions, $\alpha(\Lambda, sp)$-continuous multifunctions, almost $\alpha(\Lambda, sp)$-continuous multifunctions, almost $\beta(\Lambda, sp)$-continuous multifunctions, slightly (Λ, sp)-continuous multifunctions, (τ_1, τ_2)-continuous multifunctions, almost (τ_1, τ_2)-continuous multifunctions, weakly (τ_1, τ_2)-continuous multifunctions, weakly quasi (τ_1, τ_2)-continuous multifunctions, s-$(\tau_1, \tau_2)p$-continuous multifunctions and c-(τ_1, τ_2)-continuous multifunctions were investigated in [24], [20], [26], [21], [60], [6], [12], [25], [13], [15], [14], [18], [22], [11], [38], [17], [55], [16], [50], [39], [53], [48], [57] and [37], respectively. Noiri and Popa [43] introduced the notion of slightly m-continuous multifunctions and studied the relationships among m-continuity, almost m-continuity, weak m-continuity and slight m-continuity for multifunctions. Viriyapong et al. [58] introduced and investigated the concepts of upper and lower slightly $(\tau_1, \tau_2)\beta$-continuous multifunctions. Khampakdee et al. [36] introduced and studied the notions of upper and lower slightly $(\tau_1, \tau_2)s$-continuous multifunctions. Viriyapong et al. [56] introduced and investigated the concepts of upper and lower slightly $\alpha(\tau_1, \tau_2)$-continuous multifunctions. In this paper, we introduce the notions of upper and lower slightly $(\tau_1, \tau_2)p$-continuous multifunctions. In particular, several characterizations of upper and lower slightly $(\tau_1, \tau_2)p$-continuous multifunctions are discussed.

2. Preliminaries

Throughout the present paper, spaces (X, τ_1, τ_2) and (Y, σ_1, σ_2) (or simply X and Y) always mean bitopological spaces on which no separation axioms are assumed unless explicitly stated. Let A be a subset of a bitopological space (X, τ_1, τ_2). The closure of A and the interior of A with respect to τ_i are denoted by τ_i-Cl(A) and τ_i-Int(A), respectively, for $i = 1, 2$. A subset A of a bitopological space (X, τ_1, τ_2) is called $\tau_1\tau_2$-*closed* [27] if $A = \tau_1\text{-Cl}(\tau_2\text{-Cl}(A))$. The complement of a $\tau_1\tau_2$-closed set is called $\tau_1\tau_2$-*open*. A subset A of a bitopological space (X, τ_1, τ_2) is said to be $\tau_1\tau_2$-*clopen* [27] if A is both $\tau_1\tau_2$-open and $\tau_1\tau_2$-closed. Let A be a subset of a bitopological space (X, τ_1, τ_2). The intersection of all $\tau_1\tau_2$-closed sets of X containing A is called the $\tau_1\tau_2$-*closure* [27] of A and is denoted by $\tau_1\tau_2\text{-Cl}(A)$. The union of all $\tau_1\tau_2$-open sets of X contained in A is called the $\tau_1\tau_2$-*interior* [27] of A and is denoted by $\tau_1\tau_2\text{-Int}(A)$.

Lemma 2.1. [27] *Let A and B be subsets of a bitopological space (X, τ_1, τ_2). For the $\tau_1\tau_2$-closure, the following properties hold:*

(1) $A \subseteq \tau_1\tau_2\text{-}Cl(A)$ *and* $\tau_1\tau_2\text{-}Cl(\tau_1\tau_2\text{-}Cl(A)) = \tau_1\tau_2\text{-}Cl(A)$.
(2) *If* $A \subseteq B$, *then* $\tau_1\tau_2\text{-}Cl(A) \subseteq \tau_1\tau_2\text{-}Cl(B)$.
(3) $\tau_1\tau_2\text{-}Cl(A)$ *is* $\tau_1\tau_2$*-closed.*
(4) A *is* $\tau_1\tau_2$*-closed if and only if* $A = \tau_1\tau_2\text{-}Cl(A)$.
(5) $\tau_1\tau_2\text{-}Cl(X - A) = X - \tau_1\tau_2\text{-}Int(A)$.

A subset A of a bitopological space (X, τ_1, τ_2) is said to be $(\tau_1, \tau_2)r$-*open* [62] (resp. $(\tau_1, \tau_2)s$-*open* [24], $(\tau_1, \tau_2)p$-*open* [24], $(\tau_1, \tau_2)\beta$-*open* [24]) if $A = \tau_1\tau_2\text{-Int}(\tau_1\tau_2\text{-Cl}(A))$ (resp. $A \subseteq \tau_1\tau_2\text{-Cl}(\tau_1\tau_2\text{-Int}(A))$, $A \subseteq \tau_1\tau_2\text{-Int}(\tau_1\tau_2\text{-Cl}(A))$, $A \subseteq \tau_1\tau_2\text{-Cl}(\tau_1\tau_2\text{-Int}(\tau_1\tau_2\text{-Cl}(A)))$). The complement of a $(\tau_1, \tau_2)r$-open (resp. $(\tau_1, \tau_2)s$-open, $(\tau_1, \tau_2)p$-open, $(\tau_1, \tau_2)\beta$-open) set is said to be $(\tau_1, \tau_2)r$-*closed*, $(\tau_1, \tau_2)s$-*closed*, $(\tau_1, \tau_2)p$-*closed*, $(\tau_1, \tau_2)\beta$-*closed*. A subset A of a bitopological space (X, τ_1, τ_2) is said to be $\alpha(\tau_1, \tau_2)$-*open* [59] if $A \subseteq \tau_1\tau_2\text{-Int}(\tau_1\tau_2\text{-Cl}(\tau_1\tau_2\text{-Int}(A)))$. The complement of an $\alpha(\tau_1, \tau_2)$-open set is called $\alpha(\tau_1, \tau_2)$-*closed*. Let A be a subset of a bitopological space (X, τ_1, τ_2). The intersection of all $(\tau_1, \tau_2)p$-closed sets of X containing A is called the $(\tau_1, \tau_2)p$-*closure* of A and is denoted by $(\tau_1, \tau_2)\text{-pCl}(A)$. The union of all $(\tau_1, \tau_2)p$-open sets of X contained in A is called the $(\tau_1, \tau_2)p$-*interior* of A and is denoted by $(\tau_1, \tau_2)\text{-pInt}(A)$.

Lemma 2.2. *For subsets A and B of a bitopological space (X, τ_1, τ_2), the following properties hold:*

(1) $A \subseteq (\tau_1, \tau_2)\text{-}pCl(A)$ *and* $(\tau_1, \tau_2)\text{-}pCl((\tau_1, \tau_2)\text{-}pCl(A)) = (\tau_1, \tau_2)\text{-}pCl(A)$.
(2) *If* $A \subseteq B$, *then* $(\tau_1, \tau_2)\text{-}pCl(A) \subseteq (\tau_1, \tau_2)\text{-}pCl(B)$.
(3) $(\tau_1, \tau_2)\text{-}pCl(A)$ *is* $(\tau_1, \tau_2)p$*-closed.*
(4) A *is* $(\tau_1, \tau_2)p$*-closed if and only if* $A = (\tau_1, \tau_2)\text{-}pCl(A)$.
(5) $(\tau_1, \tau_2)\text{-}pCl(X - A) = X - (\tau_1, \tau_2)\text{-}pInt(A)$.
(6) $x \in (\tau_1, \tau_2)\text{-}pCl(A)$ *if and only if* $A \cap U \neq \emptyset$ *for every* $(\tau_1, \tau_2)p$*-open set* U *of* X *containing* x.

By a multifunction $F : X \to Y$, we mean a point-to-set correspondence from X into Y, and we always assume that $F(x) \neq \emptyset$ for all $x \in X$. For a multifunction $F : X \to Y$, following [2] we shall denote the upper and lower inverse of a set B of Y by $F^+(B)$ and $F^-(B)$, respectively, that is, $F^+(B) = \{x \in X \mid F(x) \subseteq B\}$ and $F^-(B) = \{x \in X \mid F(x) \cap B \neq \emptyset\}$.

In particular, $F^-(y) = \{x \in X \mid y \in F(x)\}$ for each point $y \in Y$. For each $A \subseteq X$, $F(A) = \cup_{x \in A} F(x)$.

3. Upper and lower slightly $(\tau_1, \tau_2)p$-continuous multifunctions

In this section, we introduce the notions of upper and lower slightly $(\tau_1, \tau_2)p$-continuous multifunctions. Moreover, we investigate some characterizations of upper and lower slightly $(\tau_1, \tau_2)p$-continuous multifunctions.

Definition 3.1. *A multifunction $F : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$ is said to be:*

(i) *upper slightly $(\tau_1, \tau_2)p$-continuous at a point $x \in X$ if for each $\sigma_1\sigma_2$-clopen set V of Y containing $F(x)$, there exists a $(\tau_1, \tau_2)p$-open set U of X containing x such that $F(U) \subseteq V$;*

(ii) *upper slightly $(\tau_1, \tau_2)p$-continuous if F has this property at each point of X.*

Theorem 3.1. *For a multifunction $F : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$, the following properties are equivalent:*

(1) *F is upper slightly $(\tau_1, \tau_2)p$-continuous;*

(2) *$F^+(V)$ is $(\tau_1, \tau_2)p$-open in X for every $\sigma_1\sigma_2$-clopen set V of Y;*

(3) *$F^-(V)$ is $(\tau_1, \tau_2)p$-closed in X for every $\sigma_1\sigma_2$-clopen set V of Y;*

(4) *for each $x \in X$ and for each $\sigma_1\sigma_2$-clopen set V of Y such that $x \in F^+(V)$, there exists a $(\tau_1, \tau_2)p$-open set U of X containing x such that $U \subseteq F^+(V)$;*

(5) *for each $x \in X$ and for each $\sigma_1\sigma_2$-clopen set V of Y such that $x \in F^+(Y - V)$, there exists a $(\tau_1, \tau_2)p$-closed set H of X such that $x \in X - H$ and $F^-(V) \subseteq H$;*

(6) *$F^-(Y - V)$ is $(\tau_1, \tau_2)p$-closed in X for every $\sigma_1\sigma_2$-clopen set V of Y;*

(7) *$F^+(Y - V)$ is $(\tau_1, \tau_2)p$-open in X for every $\sigma_1\sigma_2$-clopen set V of Y.*

Proof. (1) ⇒ (2): Let V be any $\sigma_1\sigma_2$-clopen set V of Y and $x \in F^+(V)$. Then, $F(x) \subseteq V$. Since F is upper slightly $(\tau_1, \tau_2)p$-continuous, there exists a $(\tau_1, \tau_2)p$-open set U of X containing x such that $F(U) \subseteq V$. Thus, $x \in U \subseteq F^+(V)$ and hence $x \in (\tau_1, \tau_2)$-pInt$(F^+(V))$. Therefore, we have $F^+(V) \subseteq (\tau_1, \tau_2)$-pInt$(F^+(V))$ and so $F^+(V)$ is $(\tau_1, \tau_2)p$-open in X.

(2) ⇔ (3): This follows from the fact that $F^-(Y - B) = X - F^+(B)$ for every subset B of Y.

(3) ⇔ (6) ⇔ (7): Obvious.

(2) ⇒ (1): Let $x \in X$ and V be any $\sigma_1\sigma_2$-clopen set V of Y containing $F(x)$. Then, $x \in F^+(V) = (\tau_1, \tau_2)$-pInt$(F^+(V))$. There exists a $(\tau_1, \tau_2)p$-open set U of X containing x such that $U \subseteq F^+(V)$. Thus, $F(U) \subseteq V$ and hence F is upper slightly $(\tau_1, \tau_2)p$-continuous at x. This shows that F is upper slightly $(\tau_1, \tau_2)p$-continuous.

(1) ⇔ (4) ⇔ (5): Obvious. □

Definition 3.2. *A multifunction $F : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$ is said to be:*

(i) *lower slightly $(\tau_1, \tau_2)p$-continuous at a point $x \in X$ if for each $\sigma_1\sigma_2$-clopen set V of Y such that $F(x) \cap V \neq \emptyset$, there exists a $(\tau_1, \tau_2)p$-open set U of X containing x such that $F(z) \cap V \neq \emptyset$ for each $z \in U$;*

(ii) *lower slightly $(\tau_1, \tau_2)p$-continuous if F has this property at each point of X.*

Theorem 3.2. *For a multifunction $F : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$, the following properties are equivalent:*

(1) *F is lower slightly $(\tau_1, \tau_2)p$-continuous;*
(2) *$F^-(V)$ is $(\tau_1, \tau_2)p$-open in X for every $\sigma_1\sigma_2$-clopen set V of Y;*
(3) *$F^+(V)$ is $(\tau_1, \tau_2)p$-closed in X for every $\sigma_1\sigma_2$-clopen set V of Y;*
(4) *for each $x \in X$ and for each $\sigma_1\sigma_2$-clopen set V of Y such that $x \in F^-(V)$, there exists a $(\tau_1, \tau_2)p$-open set U of X containing x such that $U \subseteq F^-(V)$;*
(5) *for each $x \in X$ and for each $\sigma_1\sigma_2$-clopen set V of Y such that $x \in F^-(Y - V)$, there exists a $(\tau_1, \tau_2)p$-closed set H of X such that $x \in X - H$ and $F^+(V) \subseteq H$;*
(6) *$F^+(Y - V)$ is $(\tau_1, \tau_2)p$-closed in X for every $\sigma_1\sigma_2$-clopen set V of Y;*
(7) *$F^-(Y - V)$ is $(\tau_1, \tau_2)p$-open in X for every $\sigma_1\sigma_2$-clopen set V of Y.*

Proof. (1) $\Rightarrow$ (2): Let V be any $\sigma_1\sigma_2$-clopen set V of Y and $x \in F^-(V)$. Then, $F(x) \cap V \neq \emptyset$. Since F is lower slightly $(\tau_1, \tau_2)p$-continuous, there exists a $(\tau_1, \tau_2)p$-open set U of X containing x such that $F(z) \cap V \neq \emptyset$ for each $z \in U$. Therefore, we have $U \subseteq F^-(V)$ and hence $x \in U \subseteq (\tau_1, \tau_2)\text{-pInt}(F^-(V))$. Thus, $F^-(V) \subseteq (\tau_1, \tau_2)\text{-pInt}(F^-(V))$ and so $F^-(V)$ is $(\tau_1, \tau_2)p$-open in X.

(2) $\Leftrightarrow$ (3): This follows from the fact that $F^-(Y - B) = X - F^+(B)$ for every subset B of Y.

(3) $\Leftrightarrow$ (6) $\Leftrightarrow$ (7): Obvious.

(2) $\Rightarrow$ (1): Let $x \in X$ and V be any $\sigma_1\sigma_2$-clopen set V of Y such that $F(x) \cap V \neq \emptyset$. Then, $x \in F^-(V)$ and $x \notin X - F^-(V) = F^+(Y - V)$. By (3), we have $x \notin (\tau_1, \tau_2)\text{-pCl}(F^+(Y - V))$ and there exists a $(\tau_1, \tau_2)p$-open set U of X containing x such that $U \cap F^+(Y - V) = \emptyset$; hence $U \subseteq F^-(V)$. Therefore, $F(z) \cap V \neq \emptyset$ for each $z \in U$ and so F is lower slightly $(\tau_1, \tau_2)p$-continuous at x. This shows that F is lower slightly $(\tau_1, \tau_2)p$-continuous.

(1) $\Leftrightarrow$ (4) $\Leftrightarrow$ (5): Obvious. □

Definition 3.3. *A function $f : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$ is called slightly $(\tau_1, \tau_2)p$-continuous at a point $x \in X$ if for each $\sigma_1\sigma_2$-clopen set V of Y containing $f(x)$, there exists a $(\tau_1, \tau_2)p$-open set U of X containing x such that $f(U) \subseteq V$. A function $f : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$ is called slightly $(\tau_1, \tau_2)p$-continuous if f has this property at each point of X.*

Corollary 3.1. *For a function $f : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$, the following properties are equivalent:*

(1) *f is slightly $(\tau_1, \tau_2)p$-continuous;*
(2) *$f^{-1}(V)$ is $(\tau_1, \tau_2)p$-open in X for every $\sigma_1\sigma_2$-clopen set V of Y;*
(3) *$f^{-1}(V)$ is $(\tau_1, \tau_2)p$-closed in X for every $\sigma_1\sigma_2$-clopen set V of Y;*
(4) *for each $x \in X$ and for each $\sigma_1\sigma_2$-clopen set V of Y containing $f(x)$, there exists a $(\tau_1, \tau_2)p$-open set U of X containing x such that $f(U) \subseteq V$.*

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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