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ALMOST (τ_1, τ_2)-CONTINUITY AND $(\tau_1, \tau_2)p$-OPEN SETS

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Abstract. This paper deals with the concept of almost (τ_1, τ_2)-continuous multifunctions. Furthermore, some characterizations of almost (τ_1, τ_2)-continuous multifunctions are investigated.

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1. Introduction

In 1968, Singal and Singal [35] introduced the concept of almost continuous functions as a generalization of continuity. Popa [34] defined almost quasi-continuous functions as a generalization of almost continuity [35] and quasi-continuity [20]. Munshi and Bassan [22] studied the notion of almost semi-continuous functions. Maheshwari et al. [19] introduced the concept of almost feebly continuous functions as a generalization of almost continuity [35]. Noiri [27] introduced and investigated the concept of almost α-continuous functions. Nasef and Noiri [23] introduced two classes of functions, namely almost precontinuous functions and almost β-continuous functions by utilizing the notions of preopen sets and β-open sets due to Mashhour et al [21] and Abd El-Monsef et al. [1], respectively. The class of almost precontinuity is a generalization of each of almost feeble continuity and almost α-continuity. The class of almost β-continuity is a generalization of almost quasi-continuity and almost semi-continuity. Keskin and Noiri [16] introduced the concept of almost b-continuous functions by utilizing the notion of b-open sets due to Andrijević [2]. The class of almost b-continuity is a generalization of almost precontinuity and almost semi-continuity. The class of almost β-continuity is a generalization of almost

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b-continuity. In [6], the authors investigated some properties of (Λ, sp)-open sets. Viriyapong and Boonpok [38] studied several characterizations of (Λ, sp)-continuous functions by using (Λ, sp)-open sets and (Λ, sp)-closed sets. Moreover, several characterizations of strongly $\theta(\Lambda, p)$-continuous functions, $\star$-continuous functions, θ-$\mathscr{I}$-continuous functions, pairwise almost M-continuous functions and almost $(\mu, \mu')^{(m,n)}$-continuous functions were presented in [36], [5], [10], [13] and [14], respectively.

In 1982, Popa [33] introduced and studied the notion of almost continuous multifunctions. Popa and Noiri [31] introduced the notion of almost quasi-continuous multifunctions. Furthermore, several characterizations of almost quasi-continuous multifunctions were investigated in [26]. Popa et al. [29] introduced the concept of almost precontinuous multifunctions. Additionally, some characterizations of almost precontinuous multifunctions were studied in [32]. Popa and Noiri [30] introduced and investigated the notion of almost α-continuous multifunctions. Noiri and Popa [25] introduced the concept of almost β-continuous multifunctions. The further characterizations of almost β-continuous multifunctions were studied in [28]. Ekici and Park [15] introduced and studied almost γ-continuous multifunctions. Noiri and Popa [24] introduced and investigated the notion of almost m-continuous multifunctions as multifunctions from a set satisfying some minimal conditions into a topological space. Laprom et al. [18] introduced and studied the notion of almost $\beta(\tau_1, \tau_2)$-continuous multifunctions. Viriyapong and Boonpok [39] introduced and investigated the concept of almost $(\tau_1, \tau_2)\alpha$-continuous multifunctions. In particular, some characterizations of almost $\star$-continuous multifunctions, almost $\beta(\star)$-continuous multifunctions, almost $(\tau_1, \tau_2)\delta$-semicontinuous multifunctions and almost weakly (τ_1, τ_2)-continuous multifunctions were established in [11], [8], [7] and [9], respectively. In this paper, we investigate some characterizations of upper and lower almost (τ_1, τ_2)-continuous multifunctions.

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* [12] if $A = \tau_1$-Cl$(\tau_2$-Cl$(A))$. The complement of a $\tau_1\tau_2$-closed set is called *$\tau_1\tau_2$-open*. 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* [12] of A and is denoted by $\tau_1\tau_2$-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* [12] of A and is denoted by $\tau_1\tau_2$-Int(A).

Lemma 1. [12] *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) $A \subseteq \tau_1\tau_2$-*Cl*(A) *and* $\tau_1\tau_2$-*Cl*$(\tau_1\tau_2$-*Cl*$(A)) = \tau_1\tau_2$-*Cl*(A).

(2) *If* $A \subseteq B$, *then* $\tau_1\tau_2$-*Cl*$(A) \subseteq \tau_1\tau_2$-*Cl*$(B)$.

(3) *$\tau_1\tau_2$-Cl(A) is $\tau_1\tau_2$-closed.*

(4) *A is $\tau_1\tau_2$-closed if and only if $A = \tau_1\tau_2$-Cl(A).*

(5) *$\tau_1\tau_2$-Cl$(X - A) = X - \tau_1\tau_2$-Int$(A)$.*

A subset A of a bitopological space (X, τ_1, τ_2) is said to be (τ_1, τ_2)*p-open* [9] (resp. $\alpha(\tau_1, \tau_2)$*-open* [37]) if $A \subseteq \tau_1\tau_2$-Int$(\tau_1\tau_2$-Cl$(A))$ (resp. $A \subseteq \tau_1\tau_2$-Int$(\tau_1\tau_2$-Cl$(\tau_1\tau_2$-Int$(A)))$). The complement of a $(\tau_1, \tau_2)p$-open (resp. $\alpha(\tau_1, \tau_2)$-open) set is called (τ_1, τ_2)*p-closed* (resp. $\alpha(\tau_1, \tau_2)$*-closed*).

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 [3] 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. Characterizations of upper and lower almost (τ_1, τ_2)-continuous multifunctions

In this section, we investigate some characterizations of upper and lower almost (τ_1, τ_2)-continuous multifunctions.

Definition 1. [17] *A multifunction $F : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$ is said to be upper almost (τ_1, τ_2)-continuous at a point $x \in X$ if for each $\sigma_1\sigma_2$-open set V of Y containing $F(x)$, there exists a $\tau_1\tau_2$-open set U of X containing x such that $F(U) \subseteq \sigma_1\sigma_2$-Int$(\sigma_1\sigma_2$-Cl$(V))$. A multifunction $F : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$ is said to be upper almost (τ_1, τ_2)-continuous if F has this property at each point of X.*

Lemma 2. [17] *For a multifunction $F : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$, the following properties are equivalent:*

(1) *F is upper almost (τ_1, τ_2)-continuous;*

(2) *$F^+(V) \subseteq \tau_1\tau_2$-Int$(F^+(\sigma_1\sigma_2$-Int$(\sigma_1\sigma_2$-Cl$(V))))$ for every $\sigma_1\sigma_2$-open set V of Y;*

(3) *$\tau_1\tau_2$-Cl$(F^-(\sigma_1\sigma_2$-Cl$(\sigma_1\sigma_2$-Int$(K)))) \subseteq F^-(K)$ for every $\sigma_1\sigma_2$-closed set K of Y;*

(4) *$\tau_1\tau_2$-Cl$(F^-(\sigma_1\sigma_2$-Cl$(\sigma_1\sigma_2$-Int$(\sigma_1\sigma_2$-Cl$(B))))) \subseteq F^-(\sigma_1\sigma_2$-Cl$(B))$ for every subset B of Y;*

(5) *$F^+(\sigma_1\sigma_2$-Int$(B)) \subseteq \tau_1\tau_2$-Int$(F^+(\sigma_1\sigma_2$-Int$(\sigma_1\sigma_2$-Cl$(\sigma_1\sigma_2$-Int$(B)))))$ for every subset B of Y;*

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

(7) *$F^-(K)$ is $\tau_1\tau_2$-closed in X for every $(\sigma_1, \sigma_2)r$-closed set K of Y.*

Theorem 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 almost (τ_1, τ_2)-continuous;*

(2) *$\tau_1\tau_2$-Cl$(F^-(\sigma_1\sigma_2$-Cl$(\sigma_1\sigma_2$-Int$(\sigma_1\sigma_2$-Cl$(V))))) \subseteq F^-(\sigma_1\sigma_2$-Cl$(V))$ for every $(\sigma_1, \sigma_2)p$-open set V of Y;*

(3) $\tau_1\tau_2$-*Cl*$(F^-(\sigma_1\sigma_2\text{-}Cl(\sigma_1\sigma_2\text{-}Int(V)))) \subseteq F^-(\sigma_1\sigma_2\text{-}Cl(V))$ *for every* $(\sigma_1, \sigma_2)p$*-open set* V *of* Y*;*

(4) $F^+(V) \subseteq \tau_1\tau_2\text{-}Int(F^+(\sigma_1\sigma_2\text{-}Int(\sigma_1\sigma_2\text{-}Cl(V))))$ *for every* $(\sigma_1, \sigma_2)p$*-open set* V *of* Y*.*

Proof. $(1) \Rightarrow (2)$: Let V be any $(\sigma_1, \sigma_2)p$-open set of Y. Then, $\sigma_1\sigma_2$-Cl(V) is $\sigma_1\sigma_2$-closed in Y and by Lemma 2, we have

$$\tau_1\tau_2\text{-Cl}(F^-(\sigma_1\sigma_2\text{-Cl}(\sigma_1\sigma_2\text{-Int}(\sigma_1\sigma_2\text{-Cl}(V))))) \subseteq F^-(\sigma_1\sigma_2\text{-Cl}(V)).$$

$(2) \Rightarrow (3)$: Let V be any $(\sigma_1, \sigma_2)p$-open set of Y. By (2),

$$\begin{aligned}&\tau_1\tau_2\text{-Cl}(F^-(\sigma_1\sigma_2\text{-Cl}(\sigma_1\sigma_2\text{-Int}(V))))\\ &\subseteq \tau_1\tau_2\text{-Cl}(F^-(\sigma_1\sigma_2\text{-Cl}(\sigma_1\sigma_2\text{-Int}(\sigma_1\sigma_2\text{-Cl}(V)))))\\ &\subseteq F^-(\sigma_1\sigma_2\text{-Cl}(V)).\end{aligned}$$

$(3) \Rightarrow (4)$: Let V be any $(\sigma_1, \sigma_2)p$-open set of Y. Thus by (3), we have

$$\begin{aligned}&X - \tau_1\tau_2\text{-Int}(F^+(\sigma_1\sigma_2\text{-Int}(\sigma_1\sigma_2\text{-Cl}(V))))\\ &= \tau_1\tau_2\text{-Cl}(X - F^+(\sigma_1\sigma_2\text{-Int}(\sigma_1\sigma_2\text{-Cl}(V))))\\ &= \tau_1\tau_2\text{-Cl}(F^-(Y - \sigma_1\sigma_2\text{-Int}(\sigma_1\sigma_2\text{-Cl}(V))))\\ &= \tau_1\tau_2\text{-Cl}(F^-(\sigma_1\sigma_2\text{-Cl}(Y - \sigma_1\sigma_2\text{-Cl}(V))))\\ &= \tau_1\tau_2\text{-Cl}(F^-(\sigma_1\sigma_2\text{-Cl}(\sigma_1\sigma_2\text{-Int}(Y - \sigma_1\sigma_2\text{-Cl}(V)))))\\ &\subseteq F^-(\sigma_1\sigma_2\text{-Cl}(Y - \sigma_1\sigma_2\text{-Cl}(V)))\\ &= F^-(Y - \sigma_1\sigma_2\text{-Int}(\sigma_1\sigma_2\text{-Cl}(V)))\\ &\subseteq F^-(Y - V)\\ &= X - F^+(V)\end{aligned}$$

and hence $F^+(V) \subseteq \tau_1\tau_2\text{-Int}(F^+(\sigma_1\sigma_2\text{-Int}(\sigma_1\sigma_2\text{-Cl}(V))))$.

$(4) \Rightarrow (1)$: Let V be any $(\sigma_1, \sigma_2)r$-open set of Y. Then, V is $(\sigma_1, \sigma_2)p$-open in Y and by (4),

$$F^+(V) \subseteq \tau_1\tau_2\text{-Int}(F^+(\sigma_1\sigma_2\text{-Int}(\sigma_1\sigma_2\text{-Cl}(V)))) = \tau_1\tau_2\text{-Int}(F^+(V)).$$

Thus, $F^+(V)$ is $\tau_1\tau_2$-open in X. It follows from Lemma 2 that F is upper almost (τ_1, τ_2)-continuous. □

Definition 2. [17] *A multifunction* $F : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$ *is said to be lower almost* (τ_1, τ_2)*-continuous at a point* $x \in X$ *if for each* $\sigma_1\sigma_2$*-open set* V *of* Y *such that* $F(x) \cap V \neq \emptyset$*, there exists a* $\tau_1\tau_2$*-open set* U *of* X *containing* x *such that* $\sigma_1\sigma_2$*-Int*$(\sigma_1\sigma_2\text{-}Cl(V)) \cap F(z) \neq \emptyset$ *for each* $z \in U$*. A multifunction* $F : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$ *is said to be lower almost* (τ_1, τ_2)*-continuous if* F *has this property at each point of* X*.*

Lemma 3. [17] *For a multifunction* $F : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$*, the following properties are equivalent:*

(1) *F is lower almost (τ_1, τ_2)-continuous;*

(2) $F^-(V) \subseteq \tau_1\tau_2\text{-}Int(F^-(\sigma_1\sigma_2\text{-}Int(\sigma_1\sigma_2\text{-}Cl(V))))$ *for every $\sigma_1\sigma_2$-open set V of Y;*

(3) $\tau_1\tau_2\text{-}Cl(F^+(\sigma_1\sigma_2\text{-}Cl(\sigma_1\sigma_2\text{-}Int(K)))) \subseteq F^+(K)$ *for every $\sigma_1\sigma_2$-closed set K of Y;*

(4) $\tau_1\tau_2\text{-}Cl(F^+(\sigma_1\sigma_2\text{-}Cl(\sigma_1\sigma_2\text{-}Int(\sigma_1\sigma_2\text{-}Cl(B))))) \subseteq F^+(\sigma_1\sigma_2\text{-}Cl(B))$ *for every subset B of Y;*

(5) $F^-(\sigma_1\sigma_2\text{-}Int(B)) \subseteq \tau_1\tau_2\text{-}Int(F^-(\sigma_1\sigma_2\text{-}Int(\sigma_1\sigma_2\text{-}Cl(\sigma_1\sigma_2\text{-}Int(B)))))$ *for every subset B of Y;*

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

(7) *$F^+(K)$ is $\tau_1\tau_2$-closed in X for every $(\sigma_1, \sigma_2)r$-closed set K of Y.*

Theorem 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 almost (τ_1, τ_2)-continuous;*

(2) $\tau_1\tau_2\text{-}Cl(F^+(\sigma_1\sigma_2\text{-}Cl(\sigma_1\sigma_2\text{-}Int(\sigma_1\sigma_2\text{-}Cl(V))))) \subseteq F^+(\sigma_1\sigma_2\text{-}Cl(V))$ *for every $(\sigma_1, \sigma_2)p$-open set V of Y;*

(3) $\tau_1\tau_2\text{-}Cl(F^+(\sigma_1\sigma_2\text{-}Cl(\sigma_1\sigma_2\text{-}Int(V)))) \subseteq F^+(\sigma_1\sigma_2\text{-}Cl(V))$ *for every $(\sigma_1, \sigma_2)p$-open set V of Y;*

(4) $F^-(V) \subseteq \tau_1\tau_2\text{-}Int(F^-(\sigma_1\sigma_2\text{-}Int(\sigma_1\sigma_2\text{-}Cl(V))))$ *for every $(\sigma_1, \sigma_2)p$-open set V of Y.*

Proof. The proof is similar to that of Theorem 1. □

Definition 3. [4] *A function $f : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$ is said to be almost (τ_1, τ_2)-continuous at a point $x \in X$ if for each $\sigma_1\sigma_2$-open set V of Y containing $f(x)$, there exists a $\tau_1\tau_2$-open set U of X containing x such that $f(U) \subseteq \sigma_1\sigma_2\text{-}Int(\sigma_1\sigma_2\text{-}Cl(V))$. A function $f : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$ is said to be almost (τ_1, τ_2)-continuous if f has this property at each point of X.*

Corollary 1. *For a function $f : (X, \tau_1, \tau_2) \to (Y, \sigma_1, \sigma_2)$, the following properties are equivalent:*

(1) *f is almost (τ_1, τ_2)-continuous;*

(2) $\tau_1\tau_2\text{-}Cl(f^{-1}(\sigma_1\sigma_2\text{-}Cl(\sigma_1\sigma_2\text{-}Int(\sigma_1\sigma_2\text{-}Cl(V))))) \subseteq f^{-1}(\sigma_1\sigma_2\text{-}Cl(V))$ *for every $(\sigma_1, \sigma_2)p$-open set V of Y;*

(3) $\tau_1\tau_2\text{-}Cl(f^{-1}(\sigma_1\sigma_2\text{-}Cl(\sigma_1\sigma_2\text{-}Int(V)))) \subseteq f^{-1}(\sigma_1\sigma_2\text{-}Cl(V))$ *for every $(\sigma_1, \sigma_2)p$-open set V of Y;*

(4) $f^{-1}(V) \subseteq \tau_1\tau_2\text{-}Int(f^{-1}(\sigma_1\sigma_2\text{-}Int(\sigma_1\sigma_2\text{-}Cl(V))))$ *for every $(\sigma_1, \sigma_2)p$-open set V of Y.*

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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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