On $\omega$-Locally Closed Sets
in Bitopological Spaces

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Abstract
The aim of this paper is to introduce a new class of closed sets called $\omega$-locally closed sets, $\omega lc^*$- sets, $\omega lc^{**}$- sets which are weaker forms of the class of locally closed sets in bitopological spaces. Using these concepts, some of the generalizations of pairwise LC-continuous maps namely, pairwise $\omega LC^*$- Continuous maps, pairwise $\omega LC^{**}$-Continuous maps and pairwise $\omega LC^{**}$-Continuous maps in bitopological spaces are introduced and studied. Several examples are provided to illustrate the behaviour of these new class of sets and maps.

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1 Introduction

The notion of locally closed set in a bitopological space was introduced by Kuratowski and Sierpinski [8]. According to Bourbaki [3], a subset $A$ of a topological space $X$ is called locally closed in $X$ if it is the intersection of an open set and a closed set in $X$.

In the year 1970, Levine [10] introduced the class of generalized closed ($g$-closed) sets in topological spaces. Using these notions, several new notions are defined in terms of $g$-closed sets of which two are $g$-continuous maps [1] and $g$-locally closed sets [2] by Balachandran et al. These two notions are defined as natural generalization of the continuous maps and locally closed sets respectively. In 1963, Kelly [7] defined a bitopological space $(X, \tau_1, \tau_2)$ to be a set $X$ equipped with two topologies $\tau_1$, $\tau_2$ on $X$ and he initiated a systematic study of bitopological spaces. Sheik John [11] defined and studied the concepts of $\omega$-locally closed sets in topological spaces in 2002. In this paper, we define the new notions of $\omega$-locally closed sets, $\omega lc^*$- sets, $\omega lc^{**}$- sets, $\omega LC^*$- continuous maps, $\omega LC^{**}$- continuous maps and $\omega LC^{***}$-continuous maps in bitopological spaces and investigate some of their properties.

2 Preliminaries

Throughout this present paper, let $X$, $Y$ and $Z$ always represent non-empty bitopological spaces $(X, \tau_1, \tau_2)$, $(Y, \sigma_1, \sigma_2)$ and $(Z, \eta_1, \eta_2)$ on which no separation axioms are assumed unless explicitly mentioned and the integers $i, j, k \in \{1, 2\}$.

If $A$ is a subset of a topological space $X$ with a topology $\tau$, then the closure of $A$ is denoted by $\tau-cl(A)$ or $cl(A)$, the interior of $A$ is denoted by $\tau-int(A)$ or $int(A)$.

Before entering into our work we recall the following definitions from various authors.

**Definition 2.1.** A subset $A$ of a topological space $(X, \tau)$ is called semi-open [9] if $A \subseteq cl(int(A))$. The complement of semi-open set is called semi-closed set. The intersection of all semi-closed sets containing $A$ is called the semi-closure [4] of $A$, and is denoted by $scl(A)$.

**Definition 2.2.** A subset $A$ of a topological space $(X, \tau)$ is called

1. generalized closed ($g$-closed) [10] set if $cl(A) \subseteq G$ whenever $A \subseteq G$ and $G$ is open in $(X, \tau)$.

2. $\omega$-closed [11] set if $cl(A) \subseteq G$ whenever $A \subseteq G$ and $G$ is semi-open in $(X, \tau)$. 
**Definition 2.3.** The intersection of all \( \omega \)-closed sets containing the set \( A \) is called \( \omega \)-closure of \( A \), and is denoted by \( \omega \text{-cl}(A) \)[11].

**Definition 2.4.** A subset \( A \) of a bitopological space \((X, \tau_1, \tau_2)\) is called \((\tau_i, \tau_j)\)-locally closed (briefly \((\tau_i, \tau_j)\)-lc) set[6] if \( A = G \cap F \), where \( G \) is \( \tau_1 \)-open and \( F \) is \( \tau_2 \)-closed in \((X, \tau_1, \tau_2)\).

**Definition 2.5.** A map \( f : (X, \tau_1, \tau_2) \rightarrow (Y, \sigma_1, \sigma_2) \) is called pairwise \( LC \)-continuous [5] if \( f^{-1}(V) \in (\tau_1, \tau_2) - LC(X) \) for every \( \sigma_1 \)-closed set \( V \) of \((Y, \sigma_1, \sigma_2)\).

# \( \omega \)-Locally Closed Sets in Bitopological Spaces

In this section, we introduce \((\tau_i, \tau_j) - \omega lc\)-sets, \((\tau_i, \tau_j) - \omega lc^*\)-sets and \((\tau_i, \tau_j) - \omega lc^{**}\)-sets and obtain relationships among them.

**Definition 3.1.** Let \( i, j \in \{1, 2\} \) be fixed integers. A subset \( A \) of a bitopological space \((X, \tau_1, \tau_2)\) is called \((\tau_i, \tau_j) - \omega \)-locally closed (briefly \((\tau_i, \tau_j) - \omega lc\)) set if \( A = S \cap F \), where \( S \) is \( \tau_1 \)-\( \omega \)-open and \( F \) is \( \tau_2 \)-\( \omega \)-closed in \((X, \tau_1, \tau_2)\).

**Definition 3.2.** A subset \( A \) of a bitopological space \((X, \tau_1, \tau_2)\) is called \((\tau_i, \tau_j) - \omega lc^*\) if there exists a \( \tau_1 \)-\( \omega \)-open set \( S \) and \( \tau_2 \)-\( \omega \)-closed set \( F \) of \((X, \tau_1, \tau_2)\) such that \( A = S \cap F \).

**Definition 3.3.** A subset \( A \) of a bitopological space \((X, \tau_1, \tau_2)\) is called \((\tau_i, \tau_j) - \omega lc^{**}\) if there exists a \( \tau_1 \)-open set \( S \) and \( \tau_2 \)-\( \omega \)-closed set \( F \) of \((X, \tau_1, \tau_2)\) such that \( A = S \cap F \).

**Remark 3.4.** If \( \tau_1 = \tau_2 = \tau \) in Definitions 3.1, 3.2 and 3.3, then \((\tau_1, \tau_2) - \omega lc\) (resp. \((\tau_1, \tau_2) - \omega lc^*\), \((\tau_1, \tau_2) - \omega lc^{**}\)) is a \( \omega lc \) (resp. \( \omega lc^*\), \( \omega lc^{**}\)) set in a topological space [11].

The collection of all \((\tau_1, \tau_2) - \omega lc\) (resp. \((\tau_1, \tau_2) - \omega lc^*, (\tau_1, \tau_2) - \omega lc^{**}\)) sets of \((X, \tau_1, \tau_2)\) will be denoted by \((\tau_1, \tau_2) - \omega LC(X)\) (resp. \((\tau_1, \tau_2) - \omega LC^*(X), (\tau_1, \tau_2) - \omega LC^{**}(X))\).

**Theorem 3.5.** Let \( A \) be a subset of a space \((X, \tau_1, \tau_2)\).

1. If \( A \in (\tau_1, \tau_2) - LC(X) \), then \( A \in (\tau_1, \tau_2) - \omega LC^*(X) \) and \( (\tau_1, \tau_2) - \omega LC^{**}(X) \).

2. If \( A \in (\tau_1, \tau_2) - \omega LC^*(X) \), then \( A \in (\tau_1, \tau_2) - \omega LC(X) \).

3. If \( A \in (\tau_1, \tau_2) - \omega LC^{**}(X) \), then \( A \in (\tau_1, \tau_2) - \omega LC(X) \).

**Proof.** Since every closed set is \( \omega \)-closed set, the proof follows. \( \square \)
Remark 3.6. The following examples show that the reverse implications of the Theorem 3.5 are not true.

Example 3.7. Let \( X = \{a, b, c\}, \tau_1 = \{X, \phi, \{a, b\}\} \) and \( \tau_2 = \{X, \phi, \{a\}\} \). Then the subset \( \{a\} \in (\tau_1, \tau_2) - \omega LC(X) \) and \( (\tau_1, \tau_2) - \omega LC^*(X) \) but \( \{a\} \notin (\tau_1, \tau_2) - \omega LC^*(X) \).

Example 3.8. Let \( X = \{a, b, c\}, \tau_1 = \{X, \phi, \{a, b\}\} \) and \( \tau_2 = \{X, \phi, \{a, b\}\} \). Then \( \{c\} \in (\tau_1, \tau_2) - \omega LC^*(X) \) but \( \{c\} \notin (\tau_1, \tau_2) - LC(X) \).

Example 3.9. Let \( X = \{a, b, c\}, \tau_1 = \{X, \phi, \{a, b\}\} \) and \( \tau_2 = \{X, \phi, \{a, b\}\} \). Then \( \{b\} \in (\tau_1, \tau_2) - \omega LC(X) \) but \( \{b\} \notin (\tau_1, \tau_2) - \omega LC^*(X) \).

Remark 3.10. The concept of \((\tau_1, \tau_2) - \omega LC^*(X)\) and \((\tau_1, \tau_2) - \omega LC^{**}(X)\) are independent of each other as seen from the following examples.

Example 3.11. In Example 3.8, the subset \( \{a\} \in (\tau_1, \tau_2) - \omega LC^*(X) \) but \( \{a\} \notin (\tau_1, \tau_2) - \omega LC^{**}(X) \).

Example 3.12. In Example 3.9, the subset \( \{b\} \in (\tau_1, \tau_2) - \omega LC^{**}(X) \) but \( \{b\} \notin (\tau_1, \tau_2) - \omega LC^*(X) \).

Theorem 3.13. Let \( A \) be a subset of a space \((X, \tau_1, \tau_2)\).

(i) If \( A \in (\tau_1, \tau_2) - \omega LC^*(X) \).

(ii) \( A = G \cap \tau_2\text{-cl}(A) \) for some \( \tau_1 - \omega\text{-open set } G \).

(iii) \( \tau_2\text{-cl}(A) - A \) is \( \tau_1 - \omega\text{-closed} \).

(iv) \( A \cup (X - \tau_2\text{-cl}(A)) \) is \( \tau_1 - \omega\text{-open} \).

Proof. (i) \( \Rightarrow \) (ii): Let \( A \in (\tau_1, \tau_2) - \omega LC^*(X) \). Then there exist \( \tau_1 - \omega\text{-open set } G \) and a \( \tau_2\text{-closed set } F \) in \((X, \tau_1, \tau_2)\) such that \( A = G \cap F \). Since \( A \subseteq G \) and \( A \subseteq \tau_2\text{-cl}(A) \), we have \( A \subseteq G \cap \tau_2\text{-cl}(A) \). Also, since \( \tau_2\text{-cl}(A) \subseteq F \), \( G \cap \tau_2\text{-cl}(A) \subseteq G \cap F = A \). Therefore \( A = G \cap \tau_2\text{-cl}(A) \).

(ii) \( \Rightarrow \) (i): Since \( G \) is \( \tau_1 - \omega\text{-open} \) and \( \tau_2\text{-cl}(A) \) is a \( \tau_2\text{-closed set} \), we have \( A = G \cap \tau_2\text{-cl}(A) \in (\tau_1, \tau_2) - \omega LC^*(X) \).

(iii) \( \Rightarrow \) (iv): Let \( F = \tau_2\text{-cl}(A) - A \). Then by (iii), \( F \) is \( \tau_1 - \omega\text{-closed} \). Now \( X - F = A \cup (X - \tau_2\text{-cl}(A)) \). Since \( (X - F) \) is \( \tau_1 - \omega\text{-open} \), we get \( A \cup (X - \tau_2\text{-cl}(A)) \) is \( \tau_1 - \omega\text{-open} \).

(iv) \( \Rightarrow \) (iii): Let \( G = A \cup (X - \tau_2\text{-cl}(A)) \). This implies that \( X - G \) is \( \tau_1 - \omega\text{-closed} \) and \( X - G = \tau_2\text{-cl}(A) - A \). Hence \( \tau_2\text{-cl}(A) - A \) is \( \tau_1 - \omega\text{-closed} \).
\[(iv) \Rightarrow (ii)\]: Let \(G = A \cup (X - \tau_2\text{-cl}(A))\). So \(G \cap \tau_2\text{-cl}(A) = A\). Hence \(A = G \cap \tau_2\text{-cl}(A)\) for some \(\tau_1 - \omega\text{-open}\) set \(G\).

\[(ii) \Rightarrow (iv)\]: Let \(A = G \cap \tau_2\text{-cl}(A)\) for some \(\tau_1 - \omega\text{-open}\) set \(G\). Then \(A \cup (X - \tau_2\text{-cl}(A)) = G\) which is \(\tau_1 - \omega\text{-open}\).

**Theorem 3.14.** Let \(A\) and \(B\) be any two subsets of a space \((X, \tau_1, \tau_2)\). If \(A \in (\tau_1, \tau_2) - \omega\text{LC}(X)\) and \(B\) is \(\tau_1 - \omega\text{-open}\) or \(\tau_2 - \omega\text{-closed}\), then \(A \cap B \in (\tau_1, \tau_2) - \omega\text{LC}(X)\).

**Proof.** Let \(A \in (\tau_1, \tau_2) - \omega\text{LC}(X)\). This implies \(A = G \cap F\), where \(G\) is \(\tau_1 - \omega\text{-open}\) and \(F\) is \(\tau_2 - \omega\text{-closed}\) in \((X, \tau_1, \tau_2)\). Now \(A \cap B = (G \cap B) \cap F\).

- **case (i):** If \(B\) is \(\tau_1 - \omega\text{-open}\), then \(G \cap B\) is also \(\tau_1 - \omega\text{-open}\) and \(F\) is \(\tau_2 - \omega\text{-closed}\) in \((X, \tau_1, \tau_2)\). Hence \(A \cap B \in (\tau_1, \tau_2) - \omega\text{LC}(X)\).

- **case (ii):** If \(B\) is \(\tau_2 - \omega\text{-closed}\), then \(A \cap B = G \cap (B \cap F)\), where \(G\) is \(\tau_1 - \omega\text{-open}\) and \(B \cap F\) is \(\tau_2 - \omega\text{-closed}\) in \((X, \tau_1, \tau_2)\). Hence \(A \cap B \in (\tau_1, \tau_2) - \omega\text{LC}(X)\).

It is clear that, the intersection of any two \((\tau_1, \tau_2) - \omega\text{lc}\)-sets is again a \((\tau_1, \tau_2) - \omega\text{lc}\)-set.

**Theorem 3.15.** If \(A, B \in (\tau_1, \tau_2) - \omega\text{LC}^*(X)\), then \(A \cap B \in (\tau_1, \tau_2) - \omega\text{LC}^*(X)\).

**Proof.** Let \(A, B \in (\tau_1, \tau_2) - \omega\text{LC}^*(X)\). Then there exist \(\tau_1 - \omega\text{-open}\) sets \(G\) and \(H\) such that \(A = G \cap \tau_2\text{-cl}(A)\) and \(B = H \cap \tau_2\text{-cl}(A)\) by Theorem 3.13. Since \(G \cap H\) is \(\tau_1 - \omega\text{-open}\) and \(A \cap B = (G \cap H) \cap (\tau_2 - \text{cl}(A) \cap \tau_2 - \text{cl}(B))\), then \(A \cap B \in (\tau_1, \tau_2) - \omega\text{LC}^*(X)\).

**Remark 3.16.** The union of any two \((\tau_1, \tau_2) - \omega\text{lc}^*\)-sets need not be a \((\tau_1, \tau_2) - \omega\text{lc}^*\)-set as seen from the following example.

**Example 3.17.** In Example 3.9, the subsets \(\{a\}, \{c\} \in (\tau_1, \tau_2) - \omega\text{LC}^*(X)\) but their union \(\{a, c\} \notin (\tau_1, \tau_2) - \omega\text{LC}^*(X)\).

**Theorem 3.18.** If \(A, B \in (\tau_1, \tau_2) - \omega\text{LC}^{**}(X)\), then \(A \cap B \in (\tau_1, \tau_2) - \omega\text{LC}^{**}(X)\).

**Proof.** The proof is similar to Theorem 3.15.

**Theorem 3.19.** If \(A \in (\tau_1, \tau_2) - \omega\text{LC}^{**}(X)\) and \(B\) is either \(\tau_2\text{-closed}\) or \(\tau_1\text{-open}\) subset of \((X, \tau_1, \tau_2)\), then \(A \cap B \in (\tau_1, \tau_2) - \omega\text{LC}^{**}(X)\).

**Proof.** Let \(A \in (\tau_1, \tau_2) - \omega\text{LC}^{**}(X)\). This implies that \(A = G \cap F\), where \(G\) is \(\tau_1 - \omega\text{-open}\) and \(F\) is \(\tau_2 - \omega\text{-closed}\). Now \(A \cap B = (G \cap F) \cap B\). If \(B\) is \(\tau_1\text{-open}\), then \(B \cap G\) is \(\tau_1\text{-open}\). Hence \(A \cap B \in (\tau_1, \tau_2) - \omega\text{LC}^{**}(X)\). If \(B\) is \(\tau_2\text{-closed}\), then \(B \cap F\) is \(\tau_2 - \omega\text{-closed}\). Therefore \(A \cap B \in (\tau_1, \tau_2) - \omega\text{LC}^{**}(X)\).  

\(\square\)
4 Pairwise $\omega LC$-Continuous and Other related Maps

In this section we introduce new class of LC-continuous maps namely, pairwise $\omega LC$-continuous maps, $\omega LC^*$-continuous maps, $\omega LC^{**}$-continuous maps, $\omega LC$- irresolute maps, $\omega LC^*$- irresolute maps and pairwise $\omega LC^{**}$- irresolute maps and investigate some of their relationship.

**Definition 4.1.** A map $f : (X, \tau_1, \tau_2) \rightarrow (Y, \sigma_1, \sigma_2)$ is called pairwise $\omega LC$-continuous (resp. pairwise $\omega LC^*$-continuous, pairwise $\omega LC^{**}$-continuous) if $f^{-1}(V) \in (\tau_1, \tau_2) - \omega LC(X)$ (resp. $f^{-1}(V) \in (\tau_1, \tau_2) - \omega LC^*(X)$, $f^{-1}(V) \in (\tau_1, \tau_2) - \omega LC^{**}(X)$) for every $\sigma_1$-closed set $V$ in $(Y, \sigma_1, \sigma_2)$.

**Definition 4.2.** A map $f : (X, \tau_1, \tau_2) \rightarrow (Y, \sigma_1, \sigma_2)$ is called pairwise $\omega LC$- irresolute (resp. pairwise $\omega LC^*$- irresolute, pairwise $\omega LC^{**}$- irresolute) if $f^{-1}(V) \in (\tau_1, \tau_2) - \omega LC(X)$ (resp. $f^{-1}(V) \in (\tau_1, \tau_2) - \omega LC^*(X)$, $f^{-1}(V) \in (\tau_1, \tau_2) - \omega LC^{**}(X)$) for every $V \in (\sigma_1, \sigma_2) - \omega LC(Y)$ (resp. $V \in (\sigma_1, \sigma_2) - \omega LC^*(Y)$, $V \in (\sigma_1, \sigma_2) - \omega LC^{**}(Y)$).

**Theorem 4.3.** Let $f : (X, \tau_1, \tau_2) \rightarrow (Y, \sigma_1, \sigma_2)$ be a map. Then the following are satisfied.

1. If $f$ is pairwise $LC$-continuous, then it is pairwise $\omega LC$-continuous (resp. pairwise $\omega LC^*$-continuous, pairwise $\omega LC^{**}$-continuous).

2. If $f$ is pairwise $\omega LC^*$-continuous, then it is pairwise $\omega LC$-continuous.

3. If $f$ is pairwise $\omega LC^{**}$-continuous, then it is pairwise $\omega LC$-continuous.

4. If $f$ is pairwise $\omega LC$- irresolute, then it is pairwise $\omega LC$-continuous.

5. If $f$ is pairwise $\omega LC^*$- irresolute, then it is pairwise $\omega LC^*$-continuous.

**Proof.** Omitted.

**Remark 4.4.** The converses of the Theorem 4.3 need not be true in general as seen from the following examples.

**Example 4.5.** Let $X = Y = \{a, b, c\}$, $\tau_1 = \{X, \phi, \{a, b\}\}$, $\tau_2 = \{X, \phi, \{a, b\}\}$ and $\sigma_1 = \{Y, \phi, \{a\}, \{b\}, \{a, b\}\}$, $\sigma_2 = \{Y, \phi, \{a\}\}$. Define a map $f : (X, \tau_1, \tau_2) \rightarrow (Y, \sigma_1, \sigma_2)$ by $f(a) = a$, $f(b) = c$ and $f(c) = b$. Then the map $f$ is pairwise $\omega LC$-continuous (resp. pairwise $\omega LC^*$-continuous, pairwise $\omega LC^{**}$-continuous) but not pairwise $LC$-continuous.
Example 4.6. Let $X = Y = \{a, b, c\}$, $\tau_1 = \{X, \phi, \{a\}, \{a, b\}\}$, $\tau_2 = \{X, \phi, \{a, b\}\}$ and $\sigma_1 = \{Y, \phi, \{a\}, \{b\}, \{a, b\}\}$, $\sigma_2 = \{Y, \phi, \{a\}\}$. Define a map $f : (X, \tau_1, \tau_2) \rightarrow (Y, \sigma_1, \sigma_2)$ by $f(a) = a$, $f(b) = c$ and $f(c) = b$. Then the map $f$ is pairwise $\omega LC$-continuous but not pairwise $\omega LC^*$-continuous and pairwise $\omega LC^{**}$-continuous.

Example 4.7. Let $X = Y = \{a, b, c\}$, $\tau_1 = \{X, \phi, \{a\}, \{a, b\}\}$, $\tau_2 = \{X, \phi, \{a\}, \{a, b\}\}$ and $\sigma_1 = \{Y, \phi, \{a\}, \{b\}, \{a, b\}\}$, $\sigma_2 = \{Y, \phi, \{a\}\}$. Then the identity map $f : (X, \tau_1, \tau_2) \rightarrow (Y, \sigma_1, \sigma_2)$ is pairwise $\omega LC$-continuous (resp. pairwise $\omega LC^*$-continuous) but not pairwise $\omega LC$-irresolute (resp. pairwise $\omega LC^*$-irresolute).

Theorem 4.8. Let $f : (X, \tau_1, \tau_2) \rightarrow (Y, \sigma_1, \sigma_2)$ and $g : (Y, \sigma_1, \sigma_2) \rightarrow (Z, \eta_1, \eta_2)$ are functions. Then the following statements are hold.

1. If $f$ is pairwise $\omega LC$-irresolute and $g$ is pairwise $\omega LC$-continuous, then $gof$ is pairwise $\omega LC$-continuous.

2. If $f$ and $g$ are pairwise $\omega LC$-irresolute, then $gof$ is pairwise $\omega LC$-irresolute.

3. If $f$ is pairwise $\omega LC^*$-irresolute and $g$ is pairwise $\omega LC^*$-continuous, then $gof$ is pairwise $\omega LC^*$-continuous.

4. If $f$ is pairwise $\omega LC^{**}$-irresolute and $g$ is pairwise $\omega LC^{**}$-continuous, then $gof$ is pairwise $\omega LC^{**}$-continuous.

Proof. Obvious. □

Remark 4.9. The composition of pairwise $\omega LC$-continuous maps need not be pairwise $\omega LC$-continuous as seen from the following example.

Example 4.10. Let $X = Y = Z = \{a, b, c\}$, $\tau_1 = \{X, \phi, \{a\}, \{a, b\}\}$, $\tau_2 = \{X, \phi, \{a\}\}$, $\sigma_1 = \{Y, \phi, \{a\}, \{b\}, \{a, b\}\}$ and $\sigma_2 = \{Y, \phi, \{a\}\}$ and $\eta_1 = \{Z, \phi, \{a\}\}$ and $\eta_2 = \{Z, \phi, \{a\}, \{b\}, \{a, b\}\}$. Define maps $f : (X, \tau_1, \tau_2) \rightarrow (Y, \sigma_1, \sigma_2)$ by $f(a) = b$, $f(b) = c$ and $f(c) = c$ and $g : (Y, \sigma_1, \sigma_2) \rightarrow (Z, \eta_1, \eta_2)$ by $g(a) = c$, $g(b) = a$ and $g(c) = b$. Then the maps $f$ and $g$ are pairwise $\omega LC$-continuous. However their composition $fog$ is not a pairwise $\omega LC$-continuous.

References


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