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# On Statistical Compactness

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Abstract. In the search of a topological property which lies somewhere between compactness and Lindelöfness, we introduce the concept of statistical compactness in this paper. We have also searched for the preservation of statistical compactness under sub-space topology and open continuous surjection. Some finite intersection like properties are also addressed here.

**Keywords:** Asymptotic density, Open cover, Compactness, Finite intersection property.

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## 1. Introduction

Natural density, often known as asymptotic density of a set $A$ is defined as,

$$\delta(A) = \lim_{n\to\infty} \frac{1}{n} |\{k \leq n : k \in A \subseteq \mathbb{N}\}|;$$

where $\mathbb{N}$ represents the set of all natural number. H. Fast [10] (also see [18]) extended the theory of typical convergence to statistical convergence while using the concept of asymptotic density. If for every $\epsilon > 0$, the set $\{k \in \mathbb{N} : \rho(x_k, l) \geq \epsilon\}$ has asymptotic density zero in a metric space $(X, \rho)$, then the

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sequence $\{x_n\}_{n\in\mathbb{N}}$ is said to statistically converge to the point $l$. Many authors such as [8, 11, 12, 13, 16, 17] utilised and extended this notion of statistical convergence which has numerous applications in diverse fields. In [15] Di Maio and Kočinac has started a chronological investigation by using the concept of statistical convergence in both topological and uniform space. Extending the works of Maio et al. [15], recently P. Bal and D. Rakshit [4] created a new type of open cover based on the interaction of an existing open cover with asymptotic density.

On the other hand covering properties like compactness, Lindelöfness of topological spaces has been a very interesting topic for the mathematicians for a long period of time. Several authors have investigated variations of compactness [3, 7, 5] such as pseudo compact space, sequentially compact space, St-compact space, as well as variations of Lindelöfness [5, 7] such as St-Lindelöf space, sequential Lindelöf space etc. In order to continue the investigations of Maio and Kočinac, we will use asymptotic density to establish a topological property that sits somewhere between compactness and Lindelöfness.

## 2. Preliminaries

Throughout the document, a space $X$ means a topological space $X$ equipped with the topology $\tau$. Otherwise declared, no separation axioms have been granted. We use [9] for standard concepts, symbols, and nomenclature. This section contains certain prerequisite notions for the readers' convenience.

A family $\mathcal{U}$ of subsets in a topological space $X$ is called cover if $\bigcup\mathcal{U} = X$. If every element of $\mathcal{U}$ is open, then $\mathcal{U}$ is called an open cover. A topological space $X$ is called compact if every open cover of $X$ has a finite sub-cover i.e., if for every open cover $\{U_s\}_{s\in\mathbb{S}}$ of the space $X$ there exists a finite set $\{s_1, s_2, s_3 \ldots, s_k\} \subseteq \mathbb{S}$ such that $X = U_{s_1} \cup U_{s_2} \cup U_{s_3} \cup \cdots \cup U_{s_k}$. Similarly a topological space $X$ is called Lindelöf if every open cover of $X$ has a countable sub-cover. It goes without saying that every compact space is a Lindelöf space, but not the other way around.

**Definition 2.1.** [9] A topological space $(X, \tau)$ is called a countably compact space if every countable open cover of $X$ has a finite sub-cover.

Every compact space is countably compact. But the space $W_0$ of all countable ordinals is countably compact but not compact (see [9]). The space $\mathbb{N}$ of all natural numbers equipped with discrete topology is Lindelöf but it is not countably compact.

**Definition 2.2.** A family $\mathcal{F} = \{F_s\}_{s\in S}$ of subsets of a set $X$ is said to have finite intersection property if $\mathcal{F} \neq \emptyset$ and and $\bigcap_{k=1}^{n} F_{s_k} \neq \emptyset$ for every finite set $\{s_1, s_2, s_3, \ldots, s_n\} \subseteq S$ (see [9]).

**Theorem 2.3.** *A topological space $X$ is compact if and only if every family of closed subsets of $X$ having the finite intersection property has non-empty intersection (***Theorem 2.3** *of* [9]*).*

## 3. On statistical compact spaces

**Definition 3.1.** A topological space $(X, \tau)$ will be called a statistical compact (in short s-compact) space if for every countable open cover $\mathcal{U} = \{U_n : n \in \mathbb{N}\}$ of $X$, there exists a sub-cover $\mathcal{V} = \{U_{m_k} : k \in \mathbb{N}\}$ such that $\delta(\{m_k : U_{m_k} \in \mathcal{V}\}) = 0$.

**Proposition 3.2.** *Every countably compact space is a s-compact space.*

*Proof.* Let $(X, \tau)$ be a countably compact space. Then every countable open cover $\mathcal{U} = \{U_n : n \in \mathbb{N}\}$ of $X$ has a finite sub-cover $\{U_{m_1}, U_{m_2}, \ldots, U_{m_k}\}$ and being a finite subset of $\mathbb{N}$, the set $\{m_1, m_2, \ldots, m_k\}$ has natural density 0. Hence $(X, \tau)$ is a s-compact space. $\square$

Example 3.3. Converse of the above Proposition 3.2 may not be true.
Consider the topological space $(X, \tau)$, where $X = [0, 1)$ and $\tau = \{[0, \alpha) : \alpha \in [0, 1]\}$. Let $\mathcal{U} = \{U_n : n \in \mathbb{N}\}$ be a non-trivial countable open cover of $X$. If $\mathcal{U}$ is a trivial open cover then $U_k = X$ for some $k \in \mathbb{N}$. So $\mathcal{V} = \{U_k\}$ is a sub-cover of $X$ and $\delta(\{k\}) = 0$ (since natural density of finite set is always 0), then we are done.

If $\mathcal{U}$ is non-trivial countable open cover of $X$, then we take a subsequence $\mathcal{U}' = \{U_{n_k} : k \in \mathbb{N}\}$ of $\mathcal{U}$ such that $U_{n_1} = U_1$ and $U_{n_{k+1}} \supseteq U_{n_k}$ which is a cover of $X$.

Such $\mathcal{U}'$ exists because if we take $U_{n_p}$ be such that for all $m > n_p$ with $U_m \not\supseteq U_{n_p}$ then $\cup\mathcal{U} = U_{n_p} \neq X$, which is a contradiction.

$\therefore \mathcal{U}'$ exists as per its construction of the topology.

Now we take a sub sequence $\mathcal{V}$ of $\mathcal{U}'$ such that $\mathcal{V} = \{U_{n_{k^2}} : k \in \mathbb{N}\}$.

Obviously $\mathcal{V}$ is a cover of $X$ and $\delta(\{n_{k^2} : k \in \mathbb{N} \text{ and } U_{n_{k^2}} \in \mathcal{U}'\}) = 0$.

$$\text{Also, } \delta(\{n_k \in \mathbb{N} \text{ and } U_{n_k} \in \mathcal{U}\}) \leq \delta(\{n_{k^2} : k \in \mathbb{N} \text{ and } U_{n_{k^2}} \in \mathcal{U}'\}) = 0$$

$\therefore (X, \tau)$ is a s-compact space.

Let us consider the open cover $\mathcal{U} = \{U_n = [0, 1 - \frac{1}{n}) : n \in \mathbb{N}\}$ and suppose $\mathbb{U}$ has a finite sub-cover say $\mathcal{V} = \{U_{n_1}, U_{n_2}, ..., U_{n_k}\}$ then there exists a $\{U_{n_p}\}$ such that $U_{n_i} \subseteq U_{n_p}, \forall U_{n_i} \in \mathcal{V}$.

$\therefore \cup\mathcal{V} = U_{n_p} = X = [0, 1 - \frac{1}{n_p}) \neq X$, which is a contradiction.

$\therefore \mathcal{U}$ does not have any finite sub-cover. So $(X, \tau)$ is not countably compact.

Example 3.4. There exists a Lindellöf space which is not s-compact.

Let, $\mathcal{B} = \{(\frac{1}{2^n}, \frac{1}{2^{n-1}}] : n \in \mathbb{N}\} \cup \{\emptyset\}$ is a base for a suitable topology on $X = (0, 1]$ and $\tau$ be the topology generated by $\mathcal{B}$.

Let $\mathcal{U}$ be an arbitrary open cover of $X$. Then there exists at least one $U_n \in \mathcal{U}$ such that, $(\frac{1}{2^n}, \frac{1}{2^{n-1}}] \subseteq U_n \in \mathcal{U}$ for each $n \in \mathbb{N}$.

Thus $\mathcal{A} = \{U_n : n \in \mathbb{N}\} \subseteq \mathcal{U}$ and $\mathcal{A}$ is a countable sub-cover of $\mathcal{U}$. Therefore, $(X, \tau)$ is a Lindelöf space.

Now consider the countable cover $\mathcal{A} = \{U_n : n \in \mathbb{N}\}$ where, $U_n = (\frac{1}{2^n}, \frac{1}{2^{n-1}}]$.

Let $\mathcal{V} = \{U_{m_k} : k \in \mathbb{N}\}$ be a sub-cover of $\mathcal{A}$ such that $\delta(\{m_k : U_{m_k} \in \mathcal{V}\}) = 0$

$\therefore \exists$ at least one $U_i$ such that $U_i \in \mathcal{A}$ but $U_i \notin \mathcal{V}$

$[\because 1 = \delta(\{n \in \mathbb{N} : U_n \in \mathcal{A}\}) > \delta(\{m_k : U_{m_k} \in \mathcal{V}\}) = 0\ ]$.

$\therefore (\frac{1}{2^i}, \frac{1}{2^{i-1}}]$ remain uncovered by $\mathcal{V}$, which is a contradiction to the fact that $\mathcal{V}$ is a sub-cover of $\mathcal{A}$.

Example 3.5. The space $W_1 = [0, \omega)$, where, $\omega_1$ is the first uncountable ordinal with the topological $\tau = \{[0, \alpha) : \alpha < \omega_1\}$ is countably compact but not Lindelöf (see [14]). Being countably compact it is s-compact.

Following arrow diagram explains the total study of this section:

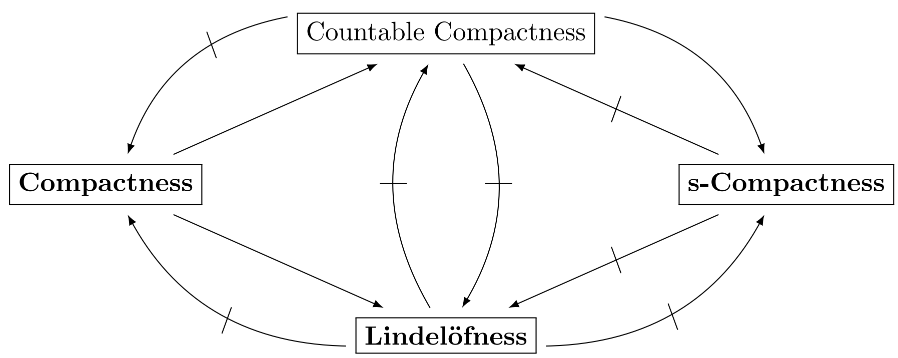


Figure 1. Relation between several covering properties.

## 4. On the subspace of s-compact space

**Theorem 4.1.** *Every closed sub-space of a s-compact space is a s-compact space.*

*Proof.* Let $(X, \tau)$ be a s-compact space and $(A, \tau_A)$ be an arbitrary closed sub-space of $(X, \tau)$. Let $\mathcal{W} = \{W_n : n \in \mathbb{N}\}$ be a countably infinite cover of $(A, \tau_A)$.

$$\therefore A = \bigcup_{n \in \mathbb{N}} W_n = \bigcup \mathcal{W}.$$

Now, for every $n \in \mathbb{N}$, there exists a $U_n \in \tau$ such that $W_n = A \cap U_n$. Therefore, $A = \bigcup_{n \in \mathbb{N}} W_n \subseteq \bigcup_{n \in \mathbb{N}} U_n$. Let us consider a countably infinite cover $\mathcal{V} = \{V_n :$

$n \in \mathbb{N}\}$ where,

$$V_n = \begin{cases} X \setminus A, & \text{if } n = 1 \\ U_{n-1}, & \text{otherwise} \end{cases}.$$

of $(X, \tau)$. But $(X, \tau)$ is s-compact space. Therefore, there exists a sub-cover $\mathcal{M} = \{V_{n_k} : k \in \mathbb{N}\}$ with $\delta(\{n_k : k \in \mathbb{N}\}) = 0$. Let, $\mathcal{M}_A = \{A \cap V_{n_k} : k \in \mathbb{N}\}$, then $\mathcal{M}_A$ is a sub-cover of $\mathcal{W}$.

Now, if $V_1 \notin \mathcal{M}$, then $\{n_k : V_{n_k} \in \mathcal{M}\} = \{n_k : A \cap V_{n_k} \in \mathcal{M}_A\}$
$\implies \delta(\{n_k : V_{n_k} \in \mathcal{M}\}) = \delta(\{n_k : A \cap V_{n_k} \in \mathcal{M}_A\}) = 0$.
If $V_1 \in \mathcal{M}$ then
$\{n_k : V_{n_k} \in \mathcal{M}\} = \{n_k - 1 : A \cap V_{n_k} \in \mathcal{M}_A\} = 0$
$\implies \delta(\{n_k : V_{n_k} \in \mathcal{M}\}) = \delta(\{n_k - 1 : A \cap V_{n_k} \in \mathcal{M}_A\}) = 0$.
Hence $(A, \tau_A)$ is a s-compact space. □

**Theorem 4.2.** *If a subspace $(A, \tau_A)$ of a topological space $(X, \tau)$ is s-compact, then for every family $\{U_n\}_{n\in\mathbb{N}}$ of open subsets of $X$ such that $A \subseteq \bigcup_{n\in\mathbb{N}} U_n$ there exists a subset $S \subseteq \mathbb{N}$ with $\delta(S) = 0$ such that $A \subseteq \bigcup_{n\in\mathbb{N}} U_n$.*

*Proof.* Let, $\{U_n\}_{n\in\mathbb{N}}$ be a family of subsets of $X$ such that $A \subseteq \bigcup_{n\in\mathbb{N}} U_n$.
$\therefore A = \bigcup_{n\in\mathbb{N}}(A \cap U_n) \implies \{A \cap U_n : n \in \mathbb{N}\}$ is an open cover of $A$ in $(A, \tau_A)$ but $(A, \tau_A)$ is s-compact.

Therefore, there exists $S \subseteq \mathbb{N}$ with $\delta(S) = 0$ such that $A = \bigcup_{n\in S}(A \cap U_n) \implies A \subseteq \bigcup_{n\in S} U_n$, and so the proof is complete. □

**Theorem 4.3.** *Let $U$ be an open subset of a topological space $(X, \tau)$. If a family $\{F_n\}_{n\in\mathbb{N}}$ of closed subsets of $X$ contains at least one s-compact set such that $\bigcap_{n\in\mathbb{N}} F_n \subseteq U$ then there exists $S \subseteq \mathbb{N}$ with $\delta(S) = 0$ such that $\bigcap_{n\in S} F_n \subseteq U$.*

*Proof.* Let, $F_{n_0}$ be the s-compact set in the family $\{F_n : n \in \mathbb{N}\}$. Since, $U \in \tau$, $X \setminus U$ is closed.

Thus $F_{n_0} \setminus U = (X \setminus U) \bigcap F_{n_0}$ is the intersection of two closed sets. Hence $F_{n_0} \setminus U$ is a closed set. Thus by Theorem 4.1, $F_{n_0} \setminus U$ is an s-compact sub-space.

Let $A = F_{n_0} \setminus U$ and consider $\{U_n = X \setminus F_n : n \in \mathbb{N}\}$ as a family of open sets.

Now $\bigcup_{n\in\mathbb{N}} U_n = X \setminus \bigcap_{n\in\mathbb{N}} F_n \supseteq X \setminus U \supseteq F_{n_0} \setminus U = A$
$\implies A \subseteq \bigcup_{n\in\mathbb{N}} U_n$. But $A$ is s-compact. Therefore by Theorem 4.2, there exist $S \subseteq \mathbb{N}$ with $\delta(S) = 0$ such that $A \subseteq \bigcup_{n\in S} U_n$.
$\implies F_{n_0} \setminus U = (X \setminus U) \bigcap F_{n_0} \subseteq \bigcup_{n\in S} U_n$
$\implies X \setminus U \subseteq \bigcup_{n\in S} X \setminus F_n = X \setminus \bigcap_{n\in S} F_n$
$\implies U \supseteq \bigcap_{n\in S} F_n$. □

**Theorem 4.4.** *If $\{(X_n, \tau_n) : n = 1, 2, ..., p\}$ in a finite collection of s-compact spaces of $X$ such that $X = \bigcup_{n=1}^{p} X_n$, then $(X, \tau)$ is an s-compact space.*

*Proof.* Let $(X_m, \tau_m)$ for $m = 1, 2, ..., p$ are s-compact subspaces of $(X, \tau)$ such that $X = \bigcup_{m=1}^{p} X_m$. Let $\mathcal{U} = \{U_n : n \in \mathbb{N}\}$ be a countable open cover of $(X, \tau)$. Then $\mathcal{U}_m = \{X_m \cap U_n : n \in \mathbb{N}\}$ are countable open covers of $(X_m, \tau_m)$ where $m = 1, 2, ..., p$.

Therefore, there exist a sub-cover $\mathcal{V}_m = \{X_m \cap U_{n_k} : k \in \mathbb{N}\}$ for each $\mathcal{U}_m$ of $(X_m, \tau_m)$ such that

$\delta(\{n_k : X_m \cap U_{n_k} \in \mathcal{V}_m\}) = 0$, for $m = 1, 2, ..., p$.

Now $\delta(\bigcup_{m=1}^{p} \{n_k : X_m \cap U_{n_k} \in \mathcal{V}_m\}) \leq \sum_{m=1}^{p} \delta(\{n_k : X_m \cap U_{n_k} \in \mathcal{V}_m\}) = 0$.

More over $X = \bigcup_{m=1}^{p} X_m \subseteq \bigcup_{m=1}^{p} \mathcal{V}_m$.

$\therefore X \subseteq \bigcup_{m=1}^{p} \mathcal{V}_m \subseteq \bigcup_{m=1}^{p} \{U_{n_k} : k \in \mathbb{N}$ and $X_m \cap U_{n_k} \in \mathcal{V}_m\} = \mathcal{W}$ (say).

Therefore, $\mathcal{W}$ is a subcover of $\mathcal{U}$ such that $\delta(\{n_k : U_{n_k} \in \mathcal{U}\}) = 0$.

Hence $(X, \tau)$ is an s-compact space. □

EXAMPLE 4.5. There exists a non s-compact topological space $(X, \tau)$ which can be expressed as union of countable s-compact subspaces.

$X_i = [i-1, i)$, where $i \in \mathbb{N}$ is a countable collection of subsets of $X = [0, \infty)$. Consider $\tau_i = \{\emptyset, X_i\}$ the indiscrete topology on $X_i$.

Then $\{(X_i, \tau_i) : i \in \mathbb{N}\}$ is a collection of s-compact spaces. Also $X = [0, \infty) = \bigcup_{i \in \mathbb{N}} X_i$ and the topology $\tau$ on $X$ is generated by $\mathcal{B} = \{[i-1, i) : i \in \mathbb{N}\}$.

For the space $(X, \tau)$, $\mathcal{U} = \{U_i = [i-1, i) : i \in \mathbb{N}\}$ is a countable open cover. If possible let $S \subset \mathbb{N}$ with $\delta(S) = 0$, such that $\bigcup_{i \in S} U_i = X$. So there exists $j \in \mathbb{N}$ and $j \notin S$. This implies that $U_j \notin \{U_i : i \in S\}$, i.e. $\bigcup_{i \in S} U_i \neq X$.

Which is a contradiction. Therefore $(X, \tau)$ is not s-compact.

**Theorem 4.6.** *A open continuous mapping of a s-compact space is also s-compact.*

*Proof.* Let $(X, \tau)$ be a s-compact space and $f : (X, \tau) \to (Y, \sigma)$ be a open continuous mapping. Let $\{G_n : n \in \mathbb{N}\}$ be a countable open cover for $Y$.

So, $\cup\{G_n : n \in \mathbb{N}\} = Y$

$\implies f^{-1}\{\cup\{G_n : n \in \mathbb{N}\}\} = f^{-1}(Y)$

$\implies \cup\{f^{-1}(G_n) : n \in \mathbb{N}\} = X$.

Also $f$ is continuous and $G_n$ is open.

$\therefore \{f^{-1}(G_n) : n \in \mathbb{N}\}$ is an open cover in $X$.

Since $X$ is s-compact space, there exists a countable sub-cover of $X$, $\{f^{-1}(G_{n_1}), f^{-1}(G_{n_2}), ...\}$ (say), where $\{n_1 < n_2 < ...\}$ and $\delta(\{n_k : k \in \mathbb{N}\}) = 0$.

$\therefore \cup\{f^{-1}(G_{n_k}) : k \in \mathbb{N}\} = X$.

Which gives $f[\cup\{f^{-1}(G_{n_k}) : k \in \mathbb{N}\}] = f(X) = Y$

$\implies \cup\{G_{n_k} : k \in \mathbb{N}\} = Y$ for $f[f^{-1}(G_{n_k})] = G_{n_k}$.

Thus $\{G_{n_k} : n \in \mathbb{N}\}$ is open sub cover of $\{G_n : n \in \mathbb{N}\}$ for Y and also $\delta(n_k) = 0$.

$\therefore (Y, \sigma)$ is also s-compact space. $\square$

Now we will introduce a finite intersection type property under the influence of natural density zero and investigate its influence on s-compactness.

**Definition 4.7.** A family $\mathcal{F} = \{F_n\}_{n\in\mathbb{N}}$ of subsets of a countable set $X$ is said to have $\delta_r$-intersection property if $\mathcal{F} \neq \emptyset$ and $\bigcap_{n\in S} F_n \neq \emptyset$ for every subset $S \subseteq \mathbb{N}$ with $\delta(S) = r$.

**Theorem 4.8.** *A Topological space $X$ is s-compact if and only if every family of countable closed subsets of $X$ which has $\delta_0$-intersection property has non empty intersection.*

*Proof.* Let $(X, \tau)$ be a s-compact space and $\{F_n\}_{n\in\mathbb{N}}$ be a arbitrary family of closed subsets of $X$ with $\delta_0$-intersection property $\bigcap\limits_{n\in\mathbb{N}} F_n = \emptyset$.

Consider $U_n = X \setminus F_n$ Then $X = X \setminus \bigcap_{n\in\mathbb{N}} F_n = \bigcup_{n\in\mathbb{N}}(X \setminus F_n) = \bigcup_{n\in\mathbb{N}} U_n$, therefore$\{U_n\}_{n\in\mathbb{N}}$ is an open cover of $X$. But $(X, \tau)$ is s-compact.

Thus there exists a subset $S \subseteq \mathbb{N}$, such that $\delta(S) = 0$ and

$\bigcup_{n\in S} U_n = X$ Now, $X = \bigcup_{n\in S} U_n = \bigcup_{n\in S} X \setminus F_n = X \setminus \bigcap_{n\in S} F_n$, therefore $\bigcap_{n\in S} F_n = \emptyset$,which is a contradiction to the fact that $\{F_n : n \in \mathbb{N}\}$ has $\delta_0$-intersection property.

Every family of closed subsets of $X$ which has $\delta_0$-intersection property has non empty intersection. Let $\mathcal{U} = \{U_n : n \in \mathbb{N}\}$ is a countable open cover of $X$.

Then, $\mathcal{F} = \{F_n = X \setminus U_n : n \in \mathbb{N}\}$ is a countable family of closed sets.

Suppose, $\bigcap_{n\in\mathbb{N}} F_n$

$= \bigcap_{n\in\mathbb{N}}(X \setminus U_n)$

$= X \setminus \bigcup_{n\in\mathbb{N}} U_n = \emptyset$

$\implies$ does not have $\delta_0$-intersection property.

Therefore, there exists $S \subseteq \mathbb{N}$ with $\delta(S) = 0$ and

$\bigcap_{n\in S} F_n = \emptyset$

$\implies \bigcap_{n\in S}(X \setminus U_n) = \emptyset$

$\implies X \setminus \bigcup_{n\in S} U_n = \emptyset$

$\implies X = \bigcup_{n\in S} U_n$, with $\delta(S) = 0$.

$\therefore (X, \tau)$ is s-compact. $\square$

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