# THE UPPER TOTAL MONOPHONIC NUMBER OF A GRAPH 

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#### Abstract

A set $M$ of vertices of a connected graph $G$ is a monophonic set if every vertex of $G$ lies on an $x$ y monophonic path for some elements $x$ and $y$ in $M$. The minimum cardinality of a monophonic set of $G$ is the monophonic number of $G$, and is denoted by $m(\mathbf{G})$. A monophonic set of cardinality $m(\mathrm{G})$. is called a $m$-set of $G$. Any monophonic set of order $m(\mathrm{G})$ is a minimum monophonic set of $G$. A monophonic set $M$ in a connected graph $G$ is called a minimal monophonic set if no proper subset of $M$ is a monophonic set of $G$. The total monophonic set $M$ of a graph $G$ is a monophonic set $M$ such that the subgraph induced by $M$ has no isolated vertices, and is denoted by $m_{t}(G)$. The upper total monophonic set of a graph $G$ is a minimal total monophonic set $M$ such that the subgraph induced by $M$ has no isolated vertices. The upper total monophonic number is the maximum cardinality of a minimal total monophonic set of $G$, and is denoted by $\mathrm{m}_{\mathrm{t}}^{+}(G)$. The upper monophonic numbers of some connected graphs are realized. It is proved that for any integers, $a, b$ and $c$ such that $2 \leq a \leq b<c$, there exists a connected graph $G$ with $m(G)=a, m_{t}(G)=b$ and $m_{t}{ }^{+}(G)=c$.

Keywords: Monophonic set, monophonic number, total monophonic number, upper total monophonic number.


## 1. Introduction

By a graph $G=(V, E)$ we mean a simple graph of order at least two. The order and size of $G$ are denoted by $p$ and $q$, respectively. For basic graph theoretic terminology, we refer to Harary [5]. The neighborhood of a vertex $v$ is the set $N(v)$ consisting of all vertices $u$ which are adjacent with $v$. The closed neighborhood of a vertex $v$ is the set $N[v]=N(v) \mathrm{U}\{v\}$. A vertex $v$ is an extreme vertex if the sub graph induced by its neighbors is complete. A vertex $v$ is a semi-extreme vertex of $G$ if the sub graph induced by its neighbors has a full degree vertex in $N(v)$. In particular, every extreme vertex is a semi - extreme vertex and a semi - extreme vertex need not be an extreme vertex.

For any two vertices $x$ and $y$ in a connected graph $G$, the distance $d(x, y)$ is the length of a shortest $x-y$ path in $G$. An $x-y$ path of length $d(x, y)$ is called an $x-y$ geodesic. A vertex $v$ is said to lie on an $x-y$ geodesic $P$ if $v$ is a vertex of $P$ including the vertices $x$ and $y$.

The closed interval $I[x, y]$ consists of all vertices lying on some $x-y$ geodesic of $G$, while for $S \subseteq$ $V, I[S]=\underset{x, y \in \mathrm{~s}}{\cup} I[x, y] . A$ set $S$ of vertices is a geodetic set if $I[S]=\mathrm{V}$, and the minimum cardinality of a geodetic set is the geodetic number $g(G)$. A geodetic set of cardinality $g(G)$ is called $a g$-set. The geodetic number of a graph was introduced in $[1,6]$ and further studied in $[2,3,4,5]$. A set $S$ of vertices of a graph $G$ is an edge geodetic set if every edge of $G$ lies on an $x-y$ geodesic for some elements $x$ and $y$ in $S$. The minimum cardinality of an edge geodetic set of $G$ is the edge geodetic number of $G$ denoted by eg $(G)$. The edge geodetic number was introduced and studied in [8]. The total edge of geodetic set of a graph $G$ is an edge geodetic set $S$ such that the subgraph induced by $S$ has no isolated vertices. The minimum cardinality of a total edge geodetic set of $G$ is the total edge geodetic number of $G$ and is denoted by $e g_{t}(G)$.

A chord of a path $u_{1}, u_{2}, \ldots, u_{\mathrm{k}}$ in $G$ is an edge $u_{i} u_{j}$ with $j \geq i+2$. A $u-v$ path $P$ is called a monophonic path of it is a chordless path. A set $M$ of vertices is a monophonic set if every vertex of $G$ lies on a monophonic path joining some pair of vertices in $M$, and the minimum cardinality of a monophonic set of $G$ is the monophonic number of $G$, and is denoted by $m(\mathrm{G})$. A monophonic set of cardinality $m(\mathrm{G})$ is called a $m$-set of $G$. Any monophonic set of order $m(\mathrm{G})$ is a minimum monophonic set of $G$. A monophonic set $M$ in a connected graph $G$ is called a minimal monophonic set if no proper subset of $M$ is a monophonic set of $G$. The monophonic number of a graph $G$ was studied in [9]. A monophonic set $M$ in a connected graph $G$ is called a minimal monophonic set if no proper subset of $M$ is a monophonic set of $G$. The upper monophonic number $\mathrm{m}^{+}(G)$ of $G$ is the maximum cardinality of a minimal set of $G$. The upper monophonic number of a graph $G$ was studied in [10]. The total monophonic set $M$ of a graph $G$ is a monophonic set $M$ such that the subgraph induced by $M$ has no isolated vertices, and is denoted by $m_{t}(G)$. The upper total monophonic set of a graph $G$ is a minimal total monophonic set $M$ such that the subgraph induced by $M$ has no isolated vertices. The upper total monophonic number is the maximum cardinality of a minimal total monophonic set of $G$, and is denoted by $\mathrm{m}_{\mathrm{t}}{ }^{+}(G)$.

The following Theorems will be used in the sequel.
Theorem 1.1 [9] : Each extreme vertex of a connected graph $G$ belongs to every monophonic set of $G$.

Theorem 1.2 [10] : Let $G$ be a connected graph with diameter $d$. Then $m(\mathrm{G}) \leq p-d+1$. Throughout this paper $G$ denotes a connected graph with atleast two vertices

## 2.UPPER TOTAL MONOPHOIC NUMBER OF A GRAPH

Definition 2.1: The total monoponic set $M$ in a connected graph $G$ is called a minimal total monophonic set of $G$ if no proper subset of $M$ is the total monophonic set of $G$. The upper total monophonic number $\mathrm{m}_{\mathrm{t}}^{+}(G)$ of $G$ is the maximum cardinality of a minimal total monophonic set of $G$.
Example 2.2: For the graph $G$ given in Figure2.1, $M_{1}=\left\{v_{2}, v_{4}\right\}, M_{2}=\left\{v_{4}, v_{6}\right\}, \quad M_{3}=\left\{v_{2}, v_{5}\right\}$ are the only three minimum monophonic sets of $G$, so that $m(G)=3$. The set $M_{4}=\left\{v_{1}, v_{3}, v_{5}\right\}$ and $M_{5}=\left\{v_{1}, v_{3}, v_{6}\right\}$ are minimalmonophonic sets of G. The set $M_{6}=\left\{v_{1}, v_{3}, v_{4}, v_{5}\right\}, M_{7}=\left\{v_{1}, v_{2}, v_{3}, v_{6}\right\}$ are the minimal total monophonic sets of $G$, so that $m_{\mathrm{t}}^{+}(G) \geq 4$. It is easily verified that no five elements of $G$ is minimal total monophonic set of $G$ and so $m_{\mathrm{t}}^{+}(G)=4$.


Figure 2.1 : G
Remark 2.3: Every minimum total monophonic set of $G$ is a minimal total monophonic set of $G$ and the converse is not true. For the graph $G$ given in figure 2.1, $M_{6}=\left\{v_{1}, v_{3}, v_{4}, v_{5}\right\}$ is a minimal total monophonic set of $G$ but not a minimum total monophonic set of $G$.
Theorem 2.4 : For any connected graph $G, 2 \leq m(G) \leq m^{+}{ }_{t}(G) \leq p$.
Proof : Any monophonic set needs atleast 2 vertices and so $m(G) \geq 2$. Since every minimal total monophonic set is a monophonic set $m(G) \leq m_{\mathrm{t}}^{+}(G)$. Also since $V(G)$ is a monophonic set of $G$, it is clear that $m_{t}^{+}(G) \leq p$. Thus $2 \leq m(G) \leq m_{\mathrm{t}}^{+}(G) \leq p$.
Theorem 2.5 : For the complete graph $K_{\mathrm{P}}(p \geq 2), m_{\mathrm{t}}^{+}\left(K_{\mathrm{p}}\right)=m^{+}\left(K_{\mathrm{p}}\right)=p$.
Proof : Since every vertx of the complete graph $K p(p \geq 2)$ is an extreme vertex, the vertex set of $K p$ is the unique monoponic set. Thus $m^{+}(K p)=m_{\mathrm{t}}^{+}(K p)$.

Theorem 2.6 : For a connected graph $G$ of order $p$, the following are equivalent:
i. $\quad m_{\mathrm{t}}{ }^{+}(G)=p$
ii. $m(G)=p$
iii. $\quad G=K_{p}$

Proof : (i)=>(ii). Let $m^{+}{ }_{t}(G)=p$. Then $M=V(G)$ is the unique minimal total monophonic set of $G$. Since no proper subset of $M$ is a monophonic set, it is clear that $M$ is the unique minimum total monopnic set of $G$ and so $m(G)=p$.
(ii) $=>$ (iii). Let $m(G)=p$. If $G \neq K_{p}$, then by theorem 1.3, $m(G) \leq p-1$, which is a condradiction. Therfore $G=K_{p}$. (iii) $\Rightarrow$ (i). Let $\mathrm{G}=\mathrm{K}_{\mathrm{p}}$. Then by Theorem 2.5, $\quad m_{t}^{+}(G)=p$.

Theorem 2.6 : Let $G$ be a connected graph with cut vertices and $M$ be a minimal monoponic set of $G$. If $v$ is a cut vertex of $G$, Then every component of $G-v$ contains an element of $M$.
Proof : Suppose that there is a component $G_{1}$ of $G-v$ such that $G_{1}$ contains no vertex of $M$. By Theorem $1.2, G_{l}$ does not contain any end vertex of $G$. Thus $G_{l}$ contains atleast one vertex, say $u$. Since $M$ is a minimal monophonic set , there exists vertices $x, y \in M$ such that $u$ lies on the $x-y$ monophonic path $P$ : $x=u_{0}, u_{1}, u_{2}, \ldots, u, \ldots, u_{t}=y$ in $G$. Let $P_{1}$ be a $x-u$ sub path of $P$ and $P_{2}$ be a $u-y$ subpath of $P$. Since $v$ is a cut vertex of $G$, both $P_{1}$ and $P_{2}$ contain $v$ so that $P$ is not a path, which is a contradiction. Thus every component of $G-v$ contains an element of $M$.
Theorem 2.7: For any connected graph $G$, no cut vertex of $G$ belongs to any minimal total monophonic set of $G$.

Proof : Let $M$ be a minimal total monophonic set of $G$ and $v \in M$ be any vertex.
We claim that $v$ is not a cut vertex of $G$. Suppose that $v$ is a cut vertex of $G$. Let $G_{1}, G_{2}, \ldots, G_{\mathrm{r}}(r \geq 2)$ be the components of $G-v$. By theorem 2.6, each component $G i,(1 \leq i \leq r)$ contains an element of $M$. We claim that $M_{I}=M-\{v\}$ is also a monophonic set of $G$. Let $x$ be a vertex of $G$. Since $M$ is a minimal monophonic set of $G, x$ lies on a monophonic path $P$ joining a pair of vertices $u$ and $v$ of $M$. Assume without loss of generality that $u \in G_{l}$. Since $v$ is adjacent to atleast one vertex of each $G_{\mathrm{i}}(1 \leq \mathrm{i} \leq r)$, assume that $v$ is adjacent to $z$ in $G_{\mathrm{k}}, k \neq 1$. Since $M$ is a monophonic set, $z$ lies on a monophonic path $Q$ joining $v$ and a vertex $w$ of $M$ such that $w$ must necessarily belongs to $G_{\mathrm{k}}$. Thus $w \neq v$. Now, since $v$ is a cut vertex of $G, P \cup Q$ is a path joining $u$ and $w$ in $M$ and thus the vertex $x$ lies on this monophonic path joining two vertices of $M_{1}$. Hence it follows that $M_{l}$ is a monophonic set of $G$. Since $M_{1} \subsetneq M$, this contradicts the fact that $M$ is a minimal total monophonic set of $G$. Hence so that no cut vertex of $G$ belongs to any minimal total monophonic set of $G$.
Theorem 2.8: For any Tree $T$ with $k$ end vertices, $m_{\mathrm{t}}{ }^{+}(T)=m^{+}(T)=m(T)=k$.
Proof: By Theorem 1.1, any monophonic set contains all the end vertices of $T$. By Theorem 2.7, no cut vertices of $T$ belongs to a minimal total monophonic set of G. Hence it follows that, the set of all end vertices of $T$ is the unique minimal total monophoni set of $T$ so that $m^{+}(T)=m^{+} t(T)=m(T)=k$.
Theorem 2.9: For a cycle $G=C_{p}(p \geq 4), m^{+} t(G)=3$.
Proof : First suppose that $G=C_{3}$. It is a complete graph, by Theorem 2.5, we have $m^{+}(G)=3$. For any cycle suppose that $m^{+}{ }_{\mathrm{t}}(G)>3$, then there exist a minimal total monophonic set $M_{1}$ such that | $M_{1} \mid \geq 3$. Now it is clear that monophonic set $M \subsetneq M_{1}$, which is a contradiction to $M_{1}$ is a minimal total monophonic set of $G$. Therfore $\quad m^{+}(G)=3$.

Theorem 2.9: For the complete bipartite graph $G=K_{m, n}$.
(i) $m_{t}^{+}(G)=2$ if $m=n=1$
(ii) $\quad m^{+}(G)=n+1$ if $m=1, n \geq 2$
(iii) $\quad m_{t}^{+}(\mathrm{G})=\min \{m, n\}+1$, if $m, n \geq 2$.

Proof: (i) and (ii) follows from Theorem 2.7. (iii) Let $m, n \geq 2$. Assume without loss of generality that $m \leq n$. First assume that $m<n$. Let $X=\left\{x_{1}, x_{2}, \ldots, x_{m}\right\}$ and $Y=\left\{y_{1}, y_{2}\right.$, .., $\left.y_{n}\right\}$ be a bipartion of $G$. Let $M=Y$. We prove that $M$ is a minimal total monophonic set of $G$. Any vertex $y_{\mathrm{i}}(1 \leq i \leq n)$ lies on a monophonic path $y_{i} y_{k}$ for $k \neq 1$ so that $M$ is a monophonic set of $G$. Let $M^{\prime \prime} \subseteq M \cdot$ Then there exists a vertex $y_{j} \in M$ such that $y_{j} \notin M^{\prime \prime} \cdot$ Then the vertex $y_{j}(1 \leq j \leq m)$ does not lie on a monophonic path joining a pair of vertices of $M^{\prime}$. Thus $M^{\prime}$ is not an monophonic set of $G$. This shows that $M$ is a minimal total monophonic set of $G$. Hence $m_{t}{ }^{+}(G) \geq n$. Let $M_{1}$ be a minimal total monophonic set of $G$ such that $\left|M_{l}\right| \geq n+1$. Since the vertex $x_{i}(1 \leq i \leq m$ and $1 \leq j \leq n)$ lies on a monophonic path $x_{i} x_{k}$ for any $k \neq i$, it follows that $X$ is monophonic set of $G$. Hence $M_{1}$ cannot contain $X$. Similarly since Y is a minimal monophonic set of G, M1 cannot contain Y also. Hence $M_{1} \subsetneq X^{\prime} \cup Y^{\prime}$ where $X^{\prime} \subsetneq X$ and $Y^{\prime} \subsetneq$ $Y$. Hence there exist a vertex $x_{i} \in X(1 \leq i \leq m)$ and a vertex $y_{j} \in Y(1 \leq i \leq n)$ such that $x_{i} y_{j} \notin M_{l}$. Hence the edge $x_{i} y_{j}$ does not lie on a monophonic path joining a pair of vertices of $M_{1}$. It follows that $M_{1}$ is not a monophonic set of $G$, which is a contradiction. Thus $M$ is a minimal total monophonic set of $G$. Hence $m_{t}^{+}(G)=\min \{m, n\}+1$.

## 3. Realization Results :

Theorem 3.1 : For positive integers $r, d$ and $k \geq d+2$ with $r \leq d \leq 2 r$, there exists a connected graph $G$ with $\operatorname{rad} G=r, \operatorname{diam} G=d$ and $m_{t}^{+}(G)=k$.

Proof : If $r=1$, then $d=1$ or 2 . For $d=1$, let $G=K_{k}$. Then by theorem 2.9

$$
m_{t}^{+}(G)=k .
$$

Now, let $r \geq 2$. We construct a graph $G$ with the desired properties as follows:
Case 1. $r=d$. Let $\mathrm{C}_{2 r}: u_{1}, u_{2}, \ldots u_{2 r}, u_{1}$ be a cycle of order $2 r$. Let $G$ be the graph obtained by adding the new vertices $v_{1}, v_{2}, \ldots, v_{k-r-2}$ and joining each $v_{i}(1 \leq i \leq k-r-2)$ with $u_{1}$ and $u_{2}$ of $c_{2 r}$. The graph $G$ is as shown in Figure 3.1


Figure 3.1 : G

It is easily verified that the eccentricity of each vertex of $G$ is $r$ so that rad

$$
G=\operatorname{diam} G=
$$ $r$. If $k=r+2$, then $G=c_{2 r}$ and so by Theorem 2.7, $m_{t}^{+}(G)=r+2=k$.

If $k>r+2$, then $M=\left\{v_{1}, v_{2}, \ldots, v_{k-r-2}\right\}$ is the set of all extreme vertices of $G$. It is clear that $M$ is not a monophonic set of $G$. Let $M_{l}=M \cup\left\{u_{1}, u_{2}, \ldots, u_{r}, u_{r+l}, u_{r+2}\right)$. It is clear that $M_{l}$ is a minimum connected monophonic set of $G$,also $\mathrm{M}_{l}$ is also a minimal connected monophonic set of $G$ so that $m^{+}(G) \geq\left|M_{l}\right|=k$.

It is clear that $M_{l}=M \cup\left\{u_{l}, u_{2}, \ldots, u_{r}, u_{r+1}, u_{r+2}\right)$ is a upper total monophonic set of $G$ so that, $m_{t}^{+}(G)=k$.

Case 2: $\mathrm{r}<\mathrm{d}$.


Figure 3.2 : G
Let $c_{2 r}: u_{1}, u_{2}, \ldots, u_{2 r}, u_{1}$ be a cycle of order $2 r$ and let $P_{d-r+1}: v_{0}, v_{1}, \ldots, v_{d-r}$ be a path of order $d-r+1$. Let $H$ be a graph obtained from $c_{2 r}$ and $P_{d-r+1}$ by identifying $u_{1}$ in $C_{2 r}$ and $v_{0}$ in $P_{d-r+1}$. Now, we add $k-$ $d-1$ new vertices $w_{1}, w_{2}, \ldots, w_{k-d-l}$ to the graph $H$ and join each vertex $w_{i}(l \leq i \leq k-d-l)$ to the vertex $v_{d-r-1}$ and also join $u_{r}$ with $u_{r+2}$, to obtain the graph $G$ in Figure 3.2. Then rad $G=r$ and diam $G=d$.

Let $M^{\prime}=\left\{v_{0}, v_{l}, \ldots, v_{d-r-1}, v_{d-r}, w_{1}, w_{2}, \ldots, w_{k-d-l}, u_{r+1}\right\}$. It is clear that $M^{\prime}$ is not a monophonic set of $G$. Let $\mathrm{M}_{1}{ }^{\prime}=M^{\prime} \cup\left\{u_{2}, u_{3}, \ldots, u_{r}\right\}$. It is clear that $\mathrm{M}_{1}{ }^{\prime}$ is a minimum connected monophonic set of $G$ and so $M_{1}^{\prime}$ is also a minimal connected monophonic set of $G . m^{+}(G)=k$. It is clear that $M_{1}^{\prime}=M^{\prime \prime} \cup\left\{u_{2}\right.$, $\left.u_{3}, \ldots, u_{r}\right\}$ is a upper total monophonic set of $G$ so that $m_{t}^{+}(G)=k$.

Theorem 3.2 : For any positive integers $2 \leq a \leq b<c$, there exists a connected graph $m(G)=a, m^{+}(G)=b, m_{t}^{+}(G)=c$.

Proof: Take a copy of star $K_{1, \mathrm{a}}$ with leaves $x_{1}, x_{2}, \ldots . . x_{\mathrm{a}}$ and the support vertex $x$. Subdivide the edge $x x_{i}$, where $1 \leq i \leq c-b-1$, calling the new vertices $y_{1}, y_{2}, \ldots, y_{c-b-1}$ where $x_{i}$ is adjacent to $y_{i}$ and $y_{i}$ is adjacent to $x$ for all $i \in\{1,2, \ldots c-b-l\}$. Let $G$ be the graph obtained by adding $b-a$ new vertices $w_{1}, w_{2}$, $\ldots w_{b-a}$ and joining each $w_{\mathrm{i}}(1 \leq i \leq b-a)$ with $x, x_{1}$. The graph $G$ is shown in figure 3.3.


Figure 3.3 : G

Let first we show that $m(G)=a$. Let $M$ be a monophonic set of $G$ and let $W=\left\{x_{2}, x_{3} \ldots x_{a}\right\}$ be the set of all extreme vertices of $G$. It is clear that $W$ is not a monophonic set of $G$. By theorem 1.1, every monophonic set of $G$ contains $W$. Clearly $M=W \mathrm{U}\left\{x_{1}\right\}$ is a monophonic set of $G$, so that $m(G)=a$.

Let $M_{l}=M \mathrm{U}\left\{w_{1}, w_{2} \ldots w_{b-a}\right\}$. Then $M_{l}$ is a minimal monophonic set of $G$. If $M_{l}$ is not a minimal monophonic set of $G$, then there is a proper subset $T$ of $M_{1}$ such that $T$ is a monophonic set of $G$. Then there exists $w \in M_{l}$ such that $w \notin T$. By theorem $1.1 w \neq x_{i}(1 \leq i \leq a)$. Therefore $w=w_{i}$ for some $i(1 \leq i \leq b-a)$. Since $w_{i} w_{j}(1 \leq i, j \leq b-a), i \neq j$ is a chord, $w_{i}$ does not lie on a monophonic path joining some vertices of $T$ and so $T$ is not a monophonic set of $G$, which is a contradiction. Thus $M_{l}$ is a minimal monophonic set of G and so $m^{+}(G)=b$.

Let $M_{2}=M_{1} \mathrm{U}\left\{y_{1}, y_{2} \ldots . y_{c-b-l}, x\right\}$. It is clear that $M_{2}$ is a minimal total monophonic set of G , so that $m_{t}^{+}(G)=c$.

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