SUFFICIENT CONDITIONS FOR MAXIMALLY EDGE-CONNECTED AND SUPER-EDGE-CONNECTED GRAPHS DEPENDING ON THE CLIQUE NUMBER

LUTZ VOLKMANN

Lehrstuhl II für Mathematik
RWTH Aachen University
52056 Aachen, Germany

e-mail: volkm@math2.rwth-aachen.de

Abstract

Let $G$ be a connected graph with minimum degree $\delta$ and edge-connectivity $\lambda$. A graph is maximally edge-connected if $\lambda = \delta$, and it is super-edge-connected if every minimum edge-cut is trivial; that is, if every minimum edge-cut consists of edges incident with a vertex of minimum degree. The clique number $\omega(G)$ of a graph $G$ is the maximum cardinality of a complete subgraph of $G$. In this paper, we show that a connected graph $G$ with clique number $\omega(G) \leq r$ is maximally edge-connected or super-edge-connected if the number of edges is large enough. These are generalizations of corresponding results for triangle-free graphs by Volkmann and Hong in 2017.

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1. Terminology and Introduction

Let $G$ be a finite and simple graph with vertex set $V = V(G)$ and edge set $E = E(G)$. The order and size of $G$ are defined by $n = n(G) = |V(G)|$ and $m = m(G) = |E(G)|$, respectively. If $N(v) = N_G(v)$ is the neighborhood of the vertex $v \in V(G)$, then we denote by $d(v) = d_G(v) = |N(v)|$ the degree of $v$ and by $\delta = \delta(G)$ the minimum degree of the graph $G$. For a subset $X \subseteq V(G)$, let $G[X]$ to denote the subgraph of $G$ induced by $X$. For two subsets $X$ and $Y$ of $V(G)$ let $[X, Y]$ be the set of edges with one endpoint in $X$ and the other one in $Y$. The clique number $\omega(G)$ of a graph $G$ is the maximum cardinality of a
complete subgraph of $G$. An edge-cut of a connected graph $G$ is a set of edges whose removal disconnects $G$. The edge connectivity $\lambda = \lambda(G)$ of a connected graph $G$ is defined as the minimum cardinality of an edge-cut over all edge-cuts of $G$. An edge-cut $S$ is a minimum edge-cut or a $\lambda$-cut if $|S| = \lambda(G)$. The inequality $\lambda(G) \leq \delta(G)$ is immediate. We call a connected graph maximally edge-connected, if $\lambda(G) = \delta(G)$. In 1981, Bauer et al. [1] proposed the concept of super-edge connectedness. A graph is called super-edge-connected or super-$\lambda$ if every minimum edge-cut is trivial; that is, if every minimum edge-cut consists of edges incident with a vertex of minimum degree. Thus every super-edge-connected graph is also maximally edge-connected.

Sufficient conditions for graphs to be maximally edge-connected or super-edge-connected were given by several authors, see for example the survey paper by Hellwig and Volkmann [3]. The starting point was an article by Chartrand [2] in 1966. He observed that if $\delta$ is large enough, then the graph is maximally edge-connected. A similar condition for super-edge-connectivity was given by Kelmans [4] six years later. Over the years, these results have been strengthened many times and in many ways.

Recently, Volkmann and Hong [6] showed that a connected graph or a connected triangle-free graph is maximally edge-connected or super-$\lambda$ if the number of edges is large enough. In particular, they received the following results.

**Theorem 1.** Let $G$ be a connected triangle-free graph of order $n \geq 2$, size $m$, minimum degree $\delta$ and edge-connectivity $\lambda$. If

$$m > \left\lfloor \frac{n^2}{4} \right\rfloor - \delta(n - 1 - 2\delta) - 1,$$

then $\lambda = \delta$.

**Theorem 2.** Let $G$ be a connected triangle-free graph of order $n$, size $m$, minimum degree $\delta \geq 3$ and edge-connectivity $\lambda$. If

$$m > \left\lfloor \frac{(n + 1)^2}{4} \right\rfloor - \delta(n + 1 - 2\delta),$$

then $G$ is super-$\lambda$.

In this paper, we will generalize Theorems 1 and 2 to connected graphs with clique number $\omega(G) \leq r$ for $r \geq 2$. Examples will demonstrate that our results are sharp.
2. Maximally Edge-Connected Graphs

The main tool of our article is the famous theorem of Turán [5].

**Theorem 3.** Let \( r \geq 1 \) be an integer, and let \( G \) be a graph of order \( n \). If the clique number \( \omega(G) \leq r \), then

\[
|E(G)| \leq \left\lfloor \frac{r - 1}{2r} \cdot n^2 \right\rfloor.
\]

**Theorem 4.** Let \( r \geq 2 \) be an integer, and let \( G \) be a connected graph of order \( n \), size \( m \), minimum degree \( \delta \geq 1 \), edge-connectivity \( \lambda \) and clique number \( \omega(G) \leq r \). If

\[
m > \left\lfloor \frac{r - 1}{2r} \left( n^2 + 2 \left\lfloor \frac{r \delta}{r - 1} \right\rfloor ^2 - 2n \left\lfloor \frac{r \delta}{r - 1} \right\rfloor \right) \right\rfloor + \delta - 1,
\]

then \( \lambda = \delta \).

**Proof.** If \( \delta = 1 \), then \( \lambda = \delta \) in every case. Thus assume in the following that \( \delta \geq 2 \). Suppose to the contrary that \( \lambda \leq \delta - 1 \). Then there exist two disjoint sets \( X, Y \subset V(G) \) with \( X \cup Y = V(G) \) and \(|X, Y| = \lambda\). Assume, without loss of generality, that \( |X| \leq |Y| \).

We first show that \( X \) contains at least \( \delta + 1 \) vertices. Otherwise, suppose that \( X \) contains at most \( \delta \) vertices. Then we obtain

\[
\delta |X| \leq \sum_{x \in X} d_G(x) \leq |X|(|X| - 1) + \lambda \leq \delta(|X| - 1) + \delta - 1.
\]

Obviously, this is a contradiction and thus \( |X| \geq \delta + 1 \). Using Theorem 3, we conclude that

(1) 
\[
|E(G[X])| \leq \left\lfloor \frac{(r - 1)|X|^2}{2r} \right\rfloor
\]

and

(2) 
\[
|E(G[Y])| \leq \left\lfloor \frac{(r - 1)|Y|^2}{2r} \right\rfloor.
\]

Next we show that \( |X| \geq \left\lfloor (r\delta)/(r - 1) \right\rfloor \). Suppose to the contrary that \( |X| \leq \left\lfloor (r\delta)/(r - 1) \right\rfloor - 1 \). Since \( 2|E(G[X])| = \sum_{x \in X} d_G(x) - \lambda \), (1) implies that

\[
|X|\delta \leq \sum_{x \in X} d_G(x) \leq 2 \left\lfloor \frac{(r - 1)|X|^2}{2r} \right\rfloor + \lambda \leq \frac{(r - 1)|X|^2}{r} + \delta - 1
\]

\[
\leq |X| \frac{r - 1}{r} \left( \left\lfloor \frac{r \delta}{r - 1} \right\rfloor - 1 \right) + \delta - 1 \leq |X| \frac{r - 1}{r} \left( \frac{r \delta}{r - 1} - 1 \right) + \delta - 1
\]

\[
= |X|\delta - \frac{r - 1}{r} |X| + \delta - 1
\]
and thus $|X| \leq \frac{r(\delta - 1)}{r}$. Using this argument once more, we arrive at

$$|X| \delta \leq \frac{(r-1)|X|^2}{r} + \delta - 1 \leq |X| \frac{r-1}{r} \cdot \frac{r(\delta - 1)}{r-1} + \delta - 1$$

and thus $|X| \leq \delta - 1$, which contradicts the fact that $|X| \geq \delta + 1$. Hence $|X| \geq \lfloor (r\delta)/(r-1) \rfloor$. Since $|X| + |Y| = n$ and $|X| \leq n/2$, the inequalities (1) and (2) lead to

$$m = |E(G[X])| + |E(G[Y])| + \lambda$$

$$\leq \left[ \frac{(r-1)|X|^2}{2r} \right] + \left[ \frac{(r-1)|Y|^2}{2r} \right] + \delta - 1$$

$$= \left[ \frac{(r-1)|X|^2}{2r} \right] + \left[ \frac{(r-1)(n - |X|)^2}{2r} \right] + \delta - 1$$

$$\leq \left[ \frac{(r-1)}{2r} \left( |X|^2 + (n - |X|)^2 \right) \right] + \delta - 1$$

$$= \left[ \frac{(r-1)}{2r} \left( n^2 + 2(|X|^2 - n|X|) \right) \right] + \delta - 1$$

$$\leq \left[ \frac{(r-1)}{2r} \left( n^2 + 2 \left( \frac{r\delta}{r-1} \right)^2 - 2n \left( \frac{r\delta}{r-1} \right) \right) \right] + \delta - 1,$$

a contradiction to the hypothesis. Thus $\lambda = \delta$.

Theorem 1 is the special case $r = 2$ of Theorem 4. The next family of graphs shows that Theorem 4 is best possible in the sense that

$$m = \left[ \frac{r-1}{2r} \left( n^2 + 2 \left( \frac{r\delta}{r-1} \right)^2 - 2n \left( \frac{r\delta}{r-1} \right) \right) \right] + \delta - 1,$$

does not guarantee $\lambda = \delta$.

**Example 5.** Let $r \geq 2$ and $q \geq 1$ be integers. Let $H_1$ and $H_2$ be two disjoint copies of the complete $r$-partite graph with $q$ vertices in each partite set. Define $H$ as the union of $H_1$ and $H_2$ by adding $\delta - 1 = q(r-1) - 1$ edges between $H_1$ and $H_2$ such that $\omega(H) \leq r$. Then $H$ has order $n = 2qr$, minimum degree $\delta = q(r-1)$ such that

$$m(H) = q^2r(r-1) + q(r-1) - 1$$

$$= \left[ \frac{r-1}{2r} \left( n^2 + 2 \left( \frac{r\delta}{r-1} \right)^2 - 2n \left( \frac{r\delta}{r-1} \right) \right) \right] + \delta - 1,$$

but obviously, $\lambda(H) = \delta(H) - 1$. 

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3. Super Edge-Connected Graphs

Theorem 6. Let $r \geq 2$ be an integer, and let $G$ be a connected graph of order $n$, size $m$, minimum degree $\delta \geq 2$, edge-connectivity $\lambda$ and $\omega(G) \leq r$. If $\delta \geq 3$ or $r \geq 3$ and

$$m > \left\lfloor \frac{r - 1}{2r} \left( n^2 + 2 \left( \left\lfloor \frac{r \delta}{r - 1} \right\rfloor - 1 \right)^2 - 2n \left( \left\lfloor \frac{r \delta}{r - 1} \right\rfloor - 1 \right) \right) \right\rfloor + \delta,$$

then $G$ is super-$\lambda$.

Proof. Suppose to the contrary that $G$ is not super-$\lambda$. Then there exist two disjoint sets $X, Y \subset V(G)$ such that $X \cup Y = V(G)$, $|X|, |Y| \geq 2$ and $|[X, Y]| = \lambda$. Assume, without loss of generality, that $2 \leq |X| \leq |Y|$.

We first show that $X$ contains at most $\delta - 1$ vertices. Otherwise, suppose that $|X| \geq \delta$, which implies $|X| \leq 1$, contradicting that $|X| \geq 2$. Thus $|X| \geq \delta$.

Next we show that $|X| \geq \lfloor (r\delta)/(r - 1) \rfloor - 1$. If $\delta = 2$ and $r \geq 3$, then

$$|X| \geq \delta = 2 \geq \lfloor (2r)/(r - 1) \rfloor - 1 = \lfloor (r\delta)/(r - 1) \rfloor - 1.$$

Let now $\delta \geq 3$. Suppose to the contrary that $X$ contains at most $\lfloor (r\delta)/(r - 1) \rfloor - 2$ vertices. Since $2|E(G[X])| = \sum_{x \in X} d_G(x) - \lambda$, we conclude from (1) that

$$|X| \delta \leq \sum_{x \in X} d_G(x) \leq \left( \frac{r - 1}{r} \right) |X|^2 + \lambda \leq \left( \frac{r - 1}{r} \right) \frac{|X|^2}{2r} + \delta$$

$$\leq |X| \left( \frac{r - 1}{r} \left( \left\lfloor \frac{r \delta}{r - 1} \right\rfloor - 2 \right) \right) + \delta \leq |X| \left( \frac{r - 1}{r} \left( \frac{r \delta}{r - 1} - 2 \right) \right) + \delta$$

$$= |X| \delta - \frac{2(r - 1)}{r} |X| + \delta$$

and thus $|X| \leq \frac{r\delta}{2(r - 1)}$. Using this argument once more, we arrive at

$$|X| \delta \leq \frac{(r - 1)|X|^2}{r} + \delta \leq |X| \frac{r - 1}{r} \cdot \frac{r\delta}{2(r - 1)} + \delta = \frac{|X| \delta}{2} + \delta$$

and thus $|X| \leq 2$, which contradicts the fact that $3 \leq \delta \leq |X|$. Hence we have shown that $|X| \geq \lfloor (r\delta)/(r - 1) \rfloor - 1$ when $\delta \geq 3$ or $r \geq 3$. Since $|X| + |Y| = n$
and \(|X| \leq n/2\), the inequalities (1) and (2) lead to
\[
m = |E(G[X])| + |E(G[Y])| + \lambda \leq \frac{(r-1)|X|^2}{2r} + \frac{(r-1)|Y|^2}{2r} + \delta
\]
= \left\lfloor \frac{(r-1)|X|^2}{2r} \right\rfloor + \left\lfloor \frac{(r-1)(n-|X|)^2}{2r} \right\rfloor + \delta
\leq \left\lfloor \frac{(r-1)}{2r} (|X|^2 + (n-|X|)^2) \right\rfloor + \delta
= \left\lfloor \frac{(r-1)}{2r} (n^2 + 2(|X|^2 - n|X|)) \right\rfloor + \delta
\leq \left\lfloor \frac{(r-1)}{2r} \left(n^2 + 2\left(\left\lfloor \frac{r\delta}{r-1} \right\rfloor - 1\right)^2 - 2n \left(\left\lfloor \frac{r\delta}{r-1} \right\rfloor - 1\right)\right) \right\rfloor + \delta,
\]
a contradiction to the hypothesis. Thus \(G\) is super-\(\lambda\).

Theorem 2 is the special case \(r = 2\) of Theorem 6. The next family of graphs shows that Theorem 6 is best possible in the sense that
\[
m = \left\lfloor \frac{r-1}{2r} \left(n^2 + 2\left(\left\lfloor \frac{r\delta}{r-1} \right\rfloor - 1\right)^2 - 2n \left(\left\lfloor \frac{r\delta}{r-1} \right\rfloor - 1\right)\right) \right\rfloor + \delta
\]
does not guarantee that the graph is super-\(\lambda\).

**Example 7.** Let \(r \geq 2\) and \(q \geq 3\) be integers. Let \(H_1\) be the complete \(r\)-partite graph with \(q-1\) vertices in one partite set and \(q\) vertices in \(r-1\) partite sets, and let \(H_2\) be the complete \(r\)-partite graph with \(q\) vertices in each partite set. Define \(H\) as the union of \(H_1\) and \(H_2\) by adding \(\delta = q(r-1)\) edges between \(H_1\) and \(H_2\) such that \(\omega(H) \leq r\) and \(\delta(H) = \delta = q(r-1)\). Then \(H\) has order \(n = 2qr - 1\), minimum degree \(\delta = q(r-1)\) such that
\[
m(H) = q^2r^2 - q^2r
= \left\lfloor \frac{r-1}{2r} \left(n^2 + 2\left(\left\lfloor \frac{r\delta}{r-1} \right\rfloor - 1\right)^2 - 2n \left(\left\lfloor \frac{r\delta}{r-1} \right\rfloor - 1\right)\right) \right\rfloor + \delta
\]
but obviously, \(H\) is not super-\(\lambda\).

Our last example demonstrates that Theorem 6 is not valid for \(\delta = 2\) and \(r = 2\) in general.

**Example 8.** Let \(q \geq 2\) be an integer, and let \(K_{q,q}\) be the complete bipartite graph with the partite sets \(X = \{x_1, x_2, \ldots, x_q\}\) and \(Y = \{y_1, y_2, \ldots, y_q\}\), and let \(u\) and \(v\) be two further vertices. Define the graph \(H\) as the union of \(K_{q,q}, u\) and
v together with the edges $uv$, $ux_1$ and $vx_2$. Then $H$ has order $n(H) = 2q + 2$, minimum degree $\delta(H) = 2$ and $\omega(H) \leq 2$. Furthermore,

$$m(H) = q^2 + 3 > q^2 - q + 4$$

$$= \left\lfloor \frac{r - 1}{2r} \left( n^2 + 2 \left( \left\lfloor \frac{r\delta}{r - 1} \right\rfloor - 1 \right) \right)^2 - 2n \left( \left\lfloor \frac{r\delta}{r - 1} \right\rfloor - 1 \right) \right\rfloor + \delta$$

but $H$ is not super-$\lambda$.

**References**


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